

VISIT...

LANZAROTE
Caliente.COM

Universe or Multiverse?

Edited by **Bernard Carr**



CAMBRIDGE

UNIVERSE OR MULTIVERSE?

Edited by

BERNARD CARR



CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521848411

© Cambridge University Press 2007

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without
the written permission of Cambridge University Press.

First published 2007

Printed in the United Kingdom at the University Press, Cambridge

A catalogue record for this publication is available from the British Library

ISBN 978-0-521-84841-1 hardback

Cambridge University Press has no responsibility for the persistence
or accuracy of URLs for external or third-party internet websites referred to
in this publication, and does not guarantee that any content on such
websites is, or will remain, accurate or appropriate.

Contents

<i>List of contributors</i>	<i>page</i> viii
<i>Preface</i>	xi
<i>Acknowledgements</i>	xiv
<i>Editorial note</i>	xv
Part I Overviews	1
1 Introduction and overview	3
<i>Bernard Carr</i>	
2 Living in the multiverse	29
<i>Steven Weinberg</i>	
3 Enlightenment, knowledge, ignorance, temptation	43
<i>Frank Wilczek</i>	
Part II Cosmology and astrophysics	55
4 Cosmology and the multiverse	57
<i>Martin J. Rees</i>	
5 The Anthropic Principle revisited	77
<i>Bernard Carr</i>	
6 Cosmology from the top down	91
<i>S. W. Hawking</i>	
7 The multiverse hierarchy	99
<i>Max Tegmark</i>	
8 The inflationary multiverse	127
<i>Andrei Linde</i>	
9 A model of anthropic reasoning: the dark to ordinary matter ratio	151
<i>Frank Wilczek</i>	

10	Anthropic predictions: the case of the cosmological constant	163
	<i>Alexander Vilenkin</i>	
11	The definition and classification of universes	181
	<i>James D. Bjorken</i>	
12	M/string theory and anthropic reasoning	191
	<i>Renata Kallosh</i>	
13	The anthropic principle, dark energy and the LHC	211
	<i>Savas Dimopoulos and Scott Thomas</i>	
	Part III Particle physics and quantum theory	219
14	Quarks, electrons and atoms in closely related universes	221
	<i>Craig J. Hogan</i>	
15	The fine-tuning problems of particle physics and anthropic mechanisms	231
	<i>John F. Donoghue</i>	
16	The anthropic landscape of string theory	247
	<i>Leonard Susskind</i>	
17	Cosmology and the many worlds interpretation of quantum mechanics	267
	<i>V. F. Mukhanov</i>	
18	Anthropic reasoning and quantum cosmology	275
	<i>James B. Hartle</i>	
19	Micro-anthropic principle for quantum theory	285
	<i>Brandon Carter</i>	
	Part IV More general philosophical issues	321
20	Scientific alternatives to the anthropic principle	323
	<i>Lee Smolin</i>	
21	Making predictions in a multiverse: conundrums, dangers, coincidences	367
	<i>Anthony Aguirre</i>	
22	Multiverses: description, uniqueness and testing	387
	<i>George Ellis</i>	
23	Predictions and tests of multiverse theories	411
	<i>Don N. Page</i>	
24	Observation selection theory and cosmological fine-tuning	431
	<i>Nick Bostrom</i>	

25	Are anthropic arguments, involving multiverses and beyond, legitimate?	445
	<i>William R. Stoeger, S. J.</i>	
26	The multiverse hypothesis: a theistic perspective	459
	<i>Robin Collins</i>	
27	Living in a simulated universe	481
	<i>John D. Barrow</i>	
28	Universes galore: where will it all end?	487
	<i>Paul Davies</i>	

List of Contributors

Anthony Aguirre

Department of Physics, University of California, Santa Cruz, California
95064, USA

John D. Barrow

DAMTP, Centre for Mathematical Sciences, Cambridge University,
Wilberforce Road, Cambridge CB3 0WA, UK

Nick Bostrom

Philosophy Faculty, Oxford University, 10 Merton Street, Oxford OX1 4JJ,
UK

James D. Bjorken

Stanford Linear Accelerator Center, 2575 Sand Hill Road, Menlo Park, CA
94025, USA

Bernard Carr

Astronomy Unit, Queen Mary, University of London, Mile End Road,
London E1 4NS, UK

Brandon Carter

Département d'Astrophysique Relativiste et Cosmologie, Observatoire de
Paris, 5 Place J. Janssen, F-92195 Meudon Cedex, France

Robin Collins

Department of Philosophy, Messiah College, P.O. Box 245, Grantham, PA
17027, USA

Paul Davies

Beyond: Center for Fundamental Concepts in Science, Arizona State University, Tempe, AZ 85281, USA

Savas Dimopoulos

Varian Physics Building, Stanford University, Stanford, CA 94305-4060, USA

John F. Donoghue

Department of Physics, University of Massachusetts, Amherst, MA 01003, USA

George Ellis

Department of Mathematics and Applied Mathematics, University of Cape Town, 7700 Rondebosch, South Africa

James B. Hartle

Physics Department, University of California, Santa Barbara, CA 93106, USA

S. W. Hawking

DAMTP, Centre for Mathematical Sciences, Cambridge University, Wilberforce Road, Cambridge CB3 0WA, UK

Craig J. Hogan

Astronomy and Physics Departments, University of Washington, Seattle, WA 98195-1580, USA

Renata Kallosh

Varian Physics Building, Stanford University, Stanford, CA 94305-4060, USA

Andrei Linde

Varian Physics Building, Stanford University, Stanford, CA 94305-4060, USA

V. F. Mukhanov

Sektion Physik, Ludwig-Maximilians-Universität, Theresienstr. 37, D-80333 Munich, Germany

Don N. Page

Department of Physics, University of Alberta, Edmonton, Alberta T6G 2J1,
Canada

Martin J. Rees

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

Lee Smolin

Perimeter Institute for Theoretical Physics, 35 King Street North, Waterloo,
Ontario N2J 2W9, Canada

William R. Stoeger

Vatican Observatory Research Group, Steward Observatory, University of
Arizona, Tucson, AZ 85719, USA

Leonard Susskind

Varian Physics Building, Stanford University, Stanford, CA 94305-4060,
USA

Max Tegmark

Department of Physics, Massachusetts Institute of Technology, Cambridge,
MA 02139, USA

Scott Thomas

Department of Physics, University of Rutgers, Piscataway, NJ 08854-8019,
USA

Alexander Vilenkin

Department of Physics and Astronomy, Tufts University, Medford, MA
02155, USA

Steven Weinberg

Physics Department, University of Texas at Austin, Austin, TX 78712, USA

Frank Wilczek

Center for Theoretical Physics, MIT 6-305, 77 Massachusetts Avenue,
Cambridge, MA 02139, USA

Preface

This book grew out of a conference entitled ‘Universe or Multiverse?’ which was held at Stanford University in March 2003 and initiated by Charles Harper of the John Templeton Foundation, which sponsored the event. Paul Davies and Andrei Linde were in charge of the scientific programme, while Mary Ann Meyers of the Templeton Foundation played the major administrative role. The meeting came at a critical point in the development of the subject and included contributions from some of the key players in the field, so I was very pleased to be invited to edit the resulting proceedings. All of the talks given at the Stanford meeting are represented in this volume and they comprise about half of the contents. These are the chapters by James Bjorken, Nick Bostrum, Robin Collins, Paul Davies, Savas Dimopoulos and Scott Thomas, Renata Kallosh, Andrei Linde, Viatcheslav Mukhanov, Martin Rees, Leonard Susskind, Max Tegmark, Alex Vilenkin, and my own second contribution.

Several years earlier, in August 2001, a meeting on a related theme – entitled ‘Anthropic Arguments in Fundamental Physics and Cosmology’ – had been held in Cambridge (UK) at the home of Martin Rees. This was also associated with the Templeton Foundation, since it was partly funded out of a grant awarded to myself, Robert Crittenden, Martin Rees and Neil Turok for a project entitled ‘Fundamental Physics and the Problem of Our Existence’. This was one of a number of awards made by the Templeton Foundation in 2000 as part of their ‘Cosmology & Fine-Tuning’ research programme. In our case, we decided to use the funds to host a series of workshops, and the 2001 meeting was the first of these.

The theme of the Cambridge meeting was somewhat broader than that of the Stanford one – it focused on the anthropic principle rather than the multiverse proposal (which might be regarded as a particular interpretation of the anthropic principle). Nevertheless, about half the talks were on the

multiverse theme, so I was keen to have these represented in the current volume. Although I had published a review of the Cambridge meeting in *Physics World* in October 2001, there had been no formal publication of the talks. In 2003 I therefore invited some of the Cambridge participants to write up their talks, albeit in updated form. I was delighted when almost everybody accepted this invitation, and their contributions represent most of the rest of the volume. These are the chapters by John Barrow, Brandon Carter, John Donoghue, George Ellis, James Hartle, Craig Hogan, Don Page, Lee Smolin, William Stoeger and Frank Wilczek.

We organized two further meetings with the aforementioned Templeton support. The second one – entitled ‘Fine-Tuning in Living Systems’ – was held at St George’s House, Windsor Castle, in August 2002. The emphasis of this was more on biology than physics, and we were much helped by having John Barrow on the Programme Committee. Although this meeting was of great interest in its own right – representing the rapidly burgeoning area of astrobiology – there was little overlap with the multiverse theme, so it is not represented in this volume. Also, the proceedings of the Windsor meeting have already been published as a special issue of the *International Journal of Astrobiology*, which appeared in April 2003.

The third meeting was held at Cambridge in September 2005. It was again hosted by Martin Rees, but this time at Trinity College, Martin having recently been appointed Master of Trinity. The title of the meeting was ‘Expectations of a Final Theory’, and on this occasion David Tong joined the Programme Committee. Most of the focus was on the exciting developments in particle physics – in particular M-theory and the string landscape scenario, which perhaps provide a plausible theoretical basis for the multiverse paradigm. Many of the talks were highly specialized and – since this volume was already about to go to press – it was anyway too late to include them. Nevertheless, the introductory talk by Steven Weinberg and the summary talk by Frank Wilczek were very general and nicely complemented the articles already written. I was therefore delighted when they both agreed – at very short notice – to produce write-ups for this volume. The article by Stephen Hawking also derives from his presentation at the Trinity meeting, although he had previously spoken at the 2001 meeting as well. It is therefore gratifying that both Cambridge meetings – and thus all three Templeton-supported meetings – are represented in this volume.

Although I have described the history behind this volume, I should emphasize that the articles are organized by topic rather than chronology. After the overview articles in Part I, I have divided them into three categories. Part II focuses on the cosmological and astrophysical aspects of the

multiverse proposal; Part III is more relevant to particle physics and quantum cosmology; and Part IV addresses more general philosophical aspects. Of course, such a clean division is not strictly possible, since some of the articles cover more than one of these areas. Indeed, it is precisely the amalgamation of the cosmological and particle physical approaches which has most powered the growing interest in the topic. Nevertheless, by and large it has been possible to divide articles according to their degree of emphasis.

Although this book evolved out of a collection of conference papers, the articles are intended to be at semi-popular level (for example at the level of *Science* or *Scientific American*) and most of the contributions have been written by the authors with that in mind. However, there is still some variation in the length and level of the articles, and some more closely resemble in technicality the original conference presentations. Where papers are more technical, I have elaborated at greater length in my introductory remarks in order to make them more accessible. In my view, the inclusion of some technical articles is desirable, because it emphasizes that the subject is a proper branch of science and not just philosophy. Also it will hopefully broaden the book's appeal to include both experts and non-experts.

As mentioned in my Introduction, the reaction of scientists to the multiverse proposal varies considerably, and some dispute that it constitutes proper science at all. It should therefore be stressed that this is not a proselitizing work, and this is signified by the question mark in the title. I did briefly consider the shorter title 'Multiverse?' or even 'Multiverse' (without the question mark), but I eventually discarded these as being too unequivocal. In fact, the authors in this volume display a broad range of attitudes to the multiverse proposal – from strong support through open-minded agnosticism to strong opposition. The proponents probably predominate numerically and they are certainly more represented in Parts II and III. However, the balance is restored in Part IV, where many of the contributors are sceptical. Therefore readers who persevere to the end of this book are unlikely to be sufficiently enlightened to answer the question raised by its title definitively. Nevertheless, it is hoped that they will be stimulated by the diversity of views expressed. Finally, it should be stressed that perhaps the most remarkable aspect of this book is that it testifies to the large number of eminent physicists who now find the subject interesting enough to be worth writing about. It is unlikely that such a volume could have been produced even a decade ago!

Bernard Carr

Acknowledgements

AQ: Please
note point
size of text
is reduced
to
9.5/11pts
to fit in
single
page.
Please
advise

This volume only exists because of indispensable contributions from various people involved in the three conferences on which it is based. First and foremost, I must acknowledge the support of the John Templeton Foundation, which hosted the Stanford meeting in 2003 and helped to fund the two Cambridge meetings in 2001 and 2005. I am especially indebted to Charles Harper, the project's initiator, and his colleague Mary Ann Meyers, director of the 'Humble Approach Initiative' programme, who played the major administrative role in the Stanford meeting and subsequently helped to oversee the progress of this volume. Special credit is also due to Paul Davies and Andrei Linde, who were in charge of the scientific programme for the Stanford meeting and conceived the title, which this book has inherited. The Templeton Foundation indirectly supported the Cambridge meetings, since these were partly funded from a Templeton grant awarded to myself, Robert Crittenden, Martin Rees and Neil Turok. I would like to thank my fellow grant-holders for a most stimulating collaboration. They undertook most of the organizational work for the Cambridge meetings, along with David Tong, who joined the Programme Committee for the 2005 meeting. I am especially indebted to Martin Rees, not only for hosting the two Cambridge meetings, but also for triggering my own interest in the subject nearly thirty years ago and for encouraging me to complete this volume. I am very grateful to various people at Cambridge University Press for helping to bring this volume to fruition: the editor Simon Capelin, who first commissioned the book; the editor John Fowler, who made some of the editorial decisions and showed great diplomacy in dealing with my various requests; the production editors Jacqui Burton and Bethan Jones; and especially the copy-editor Irene Pizzie, who went through the text so meticulously, suggested so many improvements and dealt with my continual stream of changes so patiently. Most indispensable of all were the contributors themselves, and I would like to thank them for agreeing to write up their talks and for dealing with all my editorial enquiries so patiently. Finally, I would like to thank my dear wife, Mari, for her love and support and for patiently putting up with my spending long hours in the office in order to finish this volume.

Editorial note

Although the term ‘universe’ is usually taken to mean the totality of creation, the theme of this book is the possibility that there could be other universes (either connected or disconnected from ours) in which the constants of physics (and perhaps even the laws of nature) are different. The ensemble of universes is then sometimes referred to as the ‘multiverse’, although not everybody likes that term and several alternatives are used in this volume (for example, megaverse, holocosm, and parallel worlds).

This lack of consensus on what term to use is hardly surprising, since the concept of a multiverse has arisen in many different contexts. Therefore, in my role as editor, I have not attempted to impose any particular terminology and have left authors to use whatever terms they wish. However, in so much as most authors use the word ‘universe’, albeit in different contexts, I have tried to impose uniformity in whether the first letter is upper or lower case. Although this might be regarded as a minor and rather pedantic issue, I feel that a book entitled *Universe or Multiverse?* should at least address the problem, and this distinction in notation can avoid ambiguities.

I have adopted the convention of using ‘Universe’ (with a big U) when the author is (at least implicitly) assuming that ours is the only one. When the author is (again implicitly) referring to a general member of an ensemble (or just an abstract mathematical model), the term ‘universe’ (with a small u) is generally used. The particular one we inhabit is then described as ‘our universe’, although the phrase ‘the Universe’ (with a big U) is also sometimes used. This mirrors the way in which astronomers refer to ‘our galaxy’ as ‘the Galaxy’, and allows a useful distinction to be drawn (for example) between ‘the visible Universe’ (i.e. the visible part of our universe) and ‘the visible universe’ (i.e. the universe of which a part is visible to us). The word ‘multiverse’ is always spelt with a small m, since the idea arises in different ways, so there could be more than one of them.

Some authors prefer to reserve the appellation ‘Universe’ for the ensemble itself, perhaps preserving the term ‘multiverse’ for some higher level ensemble. In this case a capital U is used. In the inflationary scenario, for example, the term ‘Universe’ would then be used to describe the whole collections of bubbles rather than any particular one. This issue also arises in the context of quantum cosmology, which implicitly assumes the ‘many worlds’ interpretation of quantum mechanics. The literature in this field commonly refers to the ‘wave-function of the Universe’, although one might argue that wave-function is really being taken over a multiverse. The title of this book can therefore be understood to refer not only to the ontological issue of whether other universes exist, but also to the etymological issue of what to call the ensemble!

Cover picture

AQ: Please confirm if the placement of Cover picture text is ok.

The picture on the cover is a tri-dimensional representation of the quadri-dimensional Calabi-Yau manifold. This describes the geometry of the extra ‘internal’ dimensions of M-theory and relates to one particular (string-inspired) multiverse scenario. I am grateful to Dr Jean-Francois ‘Colonna of CMAP/Ecole Polytechnique, FT R&D (whose website can be found at <http://www.lactamme.polytechnique.fr>) for allowing me to use this picture. The orange background represents the ‘fire’ in the equations and is a modification of a design originally conceived by Cindy King of King Design. A similar image was first used in the poster for the second meeting on which this book is based (at Stanford in 2003).

Part I

Overviews

1

Introduction and overview

Bernard Carr

Astronomy Unit, Queen Mary, University of London

1.1 Introducing the multiverse

Nearly thirty years ago I wrote an article in the journal *nature* with Martin Rees [1], bringing together all of the known constraints on the physical characteristics of the Universe – including the fine-tunings of the physical constants – which seemed to be necessary for the emergence of life. Such constraints had been dubbed ‘anthropic’ by Brandon Carter [2] – after the Greek word for ‘man’ – although it is now appreciated that this is a misnomer, since there is no reason to associate the fine-tunings with mankind in particular. We considered both the ‘weak’ anthropic principle – which accepts the laws of nature and physical constants as given and claims that the existence of observers then imposes a selection effect on where and when we observe the Universe – and the ‘strong’ anthropic principle – which (in the sense we used the term) suggests that the existence of observers imposes constraints on the physical constants themselves.

Anthropic claims – at least in their strong form – were regarded with a certain amount of disdain by physicists at the time, and in some quarters they still are. Although we took the view that any sort of explanation for the observed fine-tunings was better than none, many regarded anthropic arguments as going beyond legitimate science. The fact that some people of a theological disposition interpreted the claims as evidence for a Creator – attributing teleological significance to the strong anthropic principle – perhaps enhanced that reaction. However, attitudes have changed considerably since then. This is not so much because the status of the anthropic arguments themselves have changed – as we will see in a later chapter, some of them have become firmer and others weaker. Rather, it is because there has been a fundamental shift in the epistemological status of the anthropic principle. This arises because cosmologists have come to realize that there are many

contexts in which our universe could be just one of a (possibly infinite) ensemble of ‘parallel’ universes in which the physical constants vary. This ensemble is sometimes described as a ‘multiverse’, and this term is used pervasively in this volume (including the title). However, it must be stressed that many other terms are used – sometimes even in the same context.

These multiverse proposals have not generally been motivated by an attempt to explain the anthropic fine-tunings; most of them have arisen independently out of developments in cosmology and particle physics. Nevertheless, it now seems clear that the two concepts are inherently interlinked. For if there *are* many universes, this begs the question of why we inhabit this particular one, and – at the very least – one would have to concede that our own existence is a relevant selection effect. Indeed, since we necessarily reside in one of the life-conducive universes, the multiverse picture reduces the strong anthropic principle to an aspect of the weak one. For this reason, many physicists would regard the multiverse proposal as providing the most natural explanation of the anthropic fine-tunings.

One reason that the multiverse proposal is now popular is that it seems to be necessary in order to understand the origin of the Universe. Admittedly, cosmologists have widely differing views on how the different worlds might arise. Some invoke models in which our universe undergoes cycles of expansion and recollapse, with the constants being changed at each bounce [3]. In this case, the different universes are strung out in *time*. Others invoke the ‘inflationary’ scenario [4], in which our observable domain is part of a single ‘bubble’ which underwent an extra-fast expansion phase at some early time. There are many other bubbles, each with different laws of low-energy physics, so in this case the different universes are spread out in *space*. As a variant of this idea, Andrei Linde [5] and Alex Vilenkin [6] have invoked ‘eternal’ inflation, in which each universe is continually self-reproducing, since this predicts that there may be an infinite number of domains – all with different coupling constants. The different universes then extend in *both* space and time.

On the other hand, Stephen Hawking prefers a quantum cosmological explanation for the Universe and has objected to eternal inflation on the grounds that it extends to the infinite past and is thus incompatible with the Hartle–Hawking ‘no boundary’ proposal for the origin of the Universe [7]. This requires that the Universe started at a finite time but the initial singularity of the classical model is regularized by requiring time to become imaginary there. If one uses the path integral approach to calculate the probability of a particular history, this appears to favour very few expansion *e*-folds, so the Universe would recollapse too quickly for life to arise.

However, anthropic selection can salvage this, since one only considers histories containing observers [8].

This sort of approach to quantum cosmology only makes sense within the context of the ‘many worlds’ interpretation of quantum mechanics. This interpretation was suggested by Hugh Everett [9] in the 1950s in order to avoid having to invoke collapse of the quantum mechanical wave-function, an essential feature of the standard Copenhagen interpretation. Instead, our universe is supposed to split every time an observation is made, so one rapidly generates a huge number of parallel worlds [10]. This could be regarded as the earliest multiverse theory. Although one might want to distinguish between classical and quantum multiverses, Max Tegmark [11] has emphasized that there is no fundamental distinction between them.

Quantum theory, of course, originated out of attempts to explain the behaviour of matter on small scales. Recent developments in particle physics have led to the popularity of yet another type of multiverse. The holy grail of particle physics is to find a ‘Theory of Everything’ (TOE) which unifies all the known forces of physics. Models which unify the weak, strong and electromagnetic interactions are commonly described as ‘Grand Unified Theories’ (GUTs) and – although still unverified experimentally – have been around for nearly 30 years. Incorporating gravity into this unification has proved more difficult, but recently there have been exciting strides, with superstring theory being the currently favoured model.¹ There are various versions of superstring theory but they are amalgamated in what is termed ‘M-theory’.

Unlike the ‘Standard Model’, which excludes gravity and contains several dozen free parameters, M-theory might conceivably predict all the fundamental constants uniquely [12]. That at least has been the hope. However, recent developments suggest that this may not be the case and that the number of theories (i.e. vacuum states) could be enormous (for example 10^{500} [13]). This is sometimes described as the ‘string landscape’ scenario [14]. In this case, the dream that all the constants are uniquely determined would be dashed. There would be a huge number of possible universes (corresponding to different minima of the vacuum energy) and the values of the physical constants would be *contingent* (i.e. dependent on which universe we happen to occupy). Trying to predict the values of the constants would then be

¹ String theory posits that the fundamental constituents of matter are string-like rather than point-like, with the various types of elementary particle corresponding to different excitation states of these strings. This was originally proposed as a model of strong interactions but in the 1980s it was realized that it could be extended to a version called ‘superstring’ theory, which also includes gravity.

as forlorn as Kepler's attempts to predict the spacing of the planets in our solar system based on the properties of Platonic solids.

A crucial feature of the string landscape proposal is that the vacuum energy would be manifested as what is termed a 'cosmological constant'. This is a term in the field equations of General Relativity (denoted by Λ) originally introduced by Einstein to allow a static cosmological model but then rejected after the Universe was found to be expanding. For many subsequent decades cosmologists assumed Λ was zero, without understanding why, but a remarkable recent development has been the discovery that the expansion of the Universe is accelerating under the influence of (what at least masquerades as) a cosmological constant. One possibility is that Λ arises through quantum vacuum effects. We do not know how to calculate these, but the most natural value would be the Planck density (which is 120 orders of magnitude larger than the observed value). Indeed in the string landscape proposal, one might expect the value of Λ across the different universes to have a uniform distribution, ranging from minus to plus the Planck value. The observed value therefore seems implausibly small.

There is also another fine-tuning problem, in that the observed vacuum density is currently very similar to the matter density, a coincidence which would only apply at a particular cosmological epoch. However, as first pointed out by Steven Weinberg [15, 16], the value of Λ is constrained anthropically because galaxies could not form if it were much larger than observed. This is not the only possible explanation for the smallness of Λ , but there is a reluctant acceptance that it may be the most plausible one, which is why both string landscape and anthropic ideas are rather popular at present. The crucial issue of whether the number of vacuum states is sufficiently large and their spacing sufficiently small to satisfy the anthropic constraints is still unresolved.

It should be noted that M-theory requires there to be extra dimensions beyond the four familiar ones of space and time. Some of these may be compactified, but others may be extended, in which case, the Universe would correspond to a 4-dimensional 'brane' in a higher-dimensional 'bulk' [17, 18]. In the first versions of this theory, the cosmological constant was negative, which was incompatible with the observed acceleration of the Universe. A few years ago, however, it was realized that M-theory solutions with a positive cosmological constant are also possible [19], and this has revitalized the collaboration between cosmologists and string theorists. The notion that our universe is a brane in a higher-dimensional bulk also suggests another multiverse scenario, since there might be many other branes in the bulk. Collisions between these branes might even generate big bangs of the kind

which initiated the expansion of our own universe [20]. Indeed, some people have envisaged successive collisions producing cyclic models, and it has been claimed that this could provide another (non-anthropic) explanation for why Λ naturally tends to a value comparable to the matter density [21].

1.2 Historical perspective

We have seen how a confluence of developments in cosmology and particle physics has led to a dramatic improvement in the credibility of the multiverse proposal. In this section, we will put these developments into a historical perspective, by showing how the notion of the multiverse is just the culmination of attempts to understand the physics of the largest and smallest scales. For what we regard as the ‘Universe’ has constantly changed as scientific progress has extended observations outwards to ever larger scales and inwards to ever smaller ones. In the process, it has constantly revealed new levels of structure in the world, as well as interesting connections between the laws operating at these different levels. This section will also provide an opportunity to review some of the basic ideas of modern cosmology and particle physics, which may be useful for non-specialists.

1.2.1 The outward journey

Geocentric view

Early humans assumed that the Earth was the centre of the Universe. Astronomical events were interpreted as being much closer than they actually are, because the heavens were assumed to be the domain of the divine and therefore perfect and unchanging. The Greeks, for example, believed the Earth was at the centre of a series of ‘crystal spheres’, these becoming progressively more perfect as one moves outwards. The last one was associated with the immovable stars, so transient phenomena (like meteors and comets) were assumed to be of terrestrial origin. Even the laws of nature (such as the regularity of the seasons) seemed to be human-centred, in the sense that they could be exploited for our own purposes, so it was natural to regard them as a direct testimony to our central role in the world.

Heliocentric view

In 1542 Nicolaus Copernicus argued in *De Revolutionis Orbis* that the heliocentric picture provides a simpler explanation of planetary motions than the geocentric one, thereby removing the Earth from the centre of the Universe. The heliocentric picture had earlier been suggested by Aristarchus,

although this was regarded as blasphemous by most of his fellow Greeks, and Nicholas de Cusa, who in 1444 argued that the Universe had no centre and looks the same everywhere. Today this notion is called the Copernican or Cosmological Principle. Then in 1572 Tycho Brahe spotted a supernova in the constellation of Cassiopeia; it brightened suddenly and then dimmed over the course of a year, but the fact that its apparent position did not change as the Earth moved around the Sun implied that it was well beyond the Moon. Because this destroyed the Aristotelian view that the heavens never change, the claim was at first received sceptically. Frustrated by those who had eyes but would not see, Brahe wrote in the preface of *De Nova Stella*: ‘O crassa ingenia. O coecos coeli spectators.’ (Oh thick wits. Oh blind watchers of the sky.)

Galactocentric view

The next step occurred when Galileo Galilei used the newly invented telescope to show that not even the Sun is special. His observations of sunspots showed that it changes, and in 1610 he speculated in *The Sidereal Message* that the Milky Way – then known as a band of light in the sky but now known to be the Galaxy – consists of stars like the Sun but at such a great distance that they cannot be resolved. This not only cast doubt on the heliocentric view, but also vastly increased the size of the Universe. An equally profound shift in our view of the Universe came a few decades later with Isaac Newton’s discovery of universal gravity. By linking astronomical phenomena to those on Earth, Newton removed the special status of the heavens, and the publication of his *Principia* in 1687 led to the ‘mechanistic’ view in which the Universe is regarded as a giant machine. In the following century, the development of more powerful telescopes – coupled with Newton’s laws – enabled astronomers to understand the structure of the Milky Way. In 1750 Thomas Wright proposed that this is a disc of stars, and in 1755 Immanuel Kant speculated that some nebulae are ‘island universes’ similar to the Milky Way, raising the possibility that even the Galaxy is not so special. However, the galactocentric view persisted for several more centuries, with most astronomers still assuming that the Milky Way comprised the whole Universe. Indeed this was Einstein’s belief when he published his theory of General Relativity in 1915 and started to study its cosmological implications.

Cosmocentric view

Then in the 1920s the idea anticipated by Kant – that some of the nebulae are outside the Milky Way – began to take hold. For a while this was a

matter of intense controversy. In 1920 Heber Curtis vigorously defended the island universe theory in a famous debate with Harlow Shapley. The controversy was finally resolved in 1924 when Edwin Hubble announced that he had measured the distance to M31 using Cepheid stars. An even more dramatic revelation came in 1929, when Hubble obtained radial velocities and distance estimates for several dozen nearby galaxies, thereby discovering that all galaxies are moving away from us with a speed proportional to their distance. This is now called ‘Hubble’s law’ and it has been shown to apply out to a distance of 10 billion light-years, a region containing 100 billion galaxies. The most natural interpretation of Hubble’s law is that space itself is expanding, as indeed had been predicted by Alexander Friedmann in 1920 on the basis of general relativity. Friedmann’s model suggested that the Universe began in a state of great compression at a time in the past of order the inverse of the Hubble constant, now known to be about 14 billion years. This is the ‘Big Bang’ picture, and it received decisive support in 1965 with the discovery that the Universe is bathed in a sea of background radiation. This radiation is found to have the same temperature in every direction and to have a black-body spectrum, implying that the Universe must once have been sufficiently compressed for the radiation to have interacted with the matter. Subsequent studies by the COBE satellite confirmed that it has a perfect black-body spectrum, which firmly established the Big Bang theory as a branch of mainstream physics.

Multiverse view

Further studies of the background radiation – most notably by the WMAP satellite – have revealed the tiny temperature fluctuations associated with the density ripples which eventually led to the formation of galaxies and clusters of galaxies. The angular dependence of these ripples is exactly as predicted by the inflationary scenario, which suggests that our observable domain is just a tiny patch of a much larger universe. This was the first evidence for what Tegmark [11] describes as the ‘Level I’ multiverse. A still more dramatic revelation has been the discovery – from observations of distant supernovae – that the expansion of the Universe is accelerating. We don’t know for sure what is causing this, but it is probably related to the vacuum energy density. As described in Section 1.1, the low value of this density may indicate that there exist many other universes with different vacuum states, so this may be evidence for Tegmark’s ‘Level II’ multiverse.

This brief historical review of developments on the outer front illustrates that the longer we have studied the Universe, the larger it has become. Indeed, the multiverse might be regarded as just one more step in the sequence of expanding vistas opened up by cosmological progress (from geocentric to heliocentric to galactocentric to cosmocentric). More conservative cosmologists might prefer to maintain the cosmocentric view that ours is the only Universe, but perhaps the tide of history is against them.

1.2.2 *The inward journey*

Equally dramatic changes of perspective have come from revelations on the inward front, with the advent of atomic theory in the eighteenth century, the discovery of subatomic particles at the start of the twentieth century and the advent of quantum theory shortly thereafter. The crucial achievement of the inward journey is that it has revealed that everything in the Universe is made up of a few fundamental particles and that these interact through four forces: gravity, electromagnetism, the weak force and the strong force. These interactions have different strengths and characteristics, and it used to be thought that they operated independently. However, it is now thought that some (and possibly all) of them can be unified as part of a single interaction.

Figure 1.1 illustrates that the history of physics might be regarded as the history of this unification. Electricity and magnetism were combined by Maxwell's theory of electromagnetism in the nineteenth century. The electromagnetic force was then combined with the weak force in the (now experimentally confirmed) electroweak theory in the 1970s. Theorists have subsequently merged the electroweak force with the strong force as part of the Grand Unified Theory (GUT), although this has still not been verified experimentally. As discussed in Section 1.1, the final (and as yet incomplete) step is the unification with gravity, as attempted by string theory or M-theory.

A remarkable feature of these theories is that the Universe may have more than the three dimensions of space that we actually observe, with the extra dimensions being compactified on the Planck scale (the distance of 10^{-33} cm at which quantum gravity effects become important), so that we do not notice them. In M-theory itself, the total number of dimensions (including time) is eleven, with 4-dimensional physics emerging from the way in which the extra dimensions are compactified (described by what is called a Calabi–Yau manifold). The discovery of dark dimensions through particle physics shakes our view of the nature of reality just as profoundly as the discovery of dark energy through cosmology. Indeed, we saw in Section 1.1 that there may be an intimate link between these ideas.

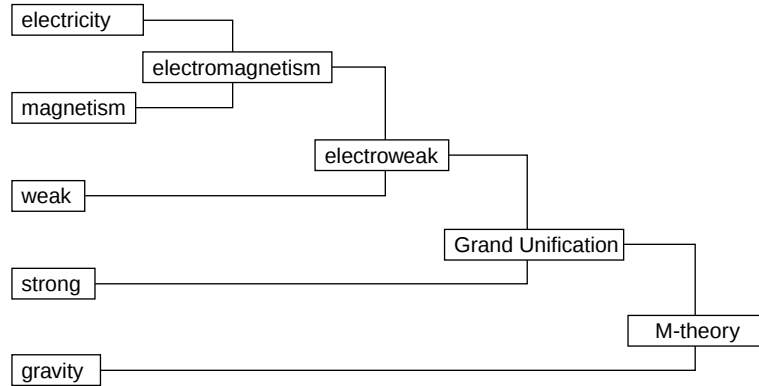
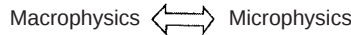


Fig. 1.1. This shows the successive steps by which physics has attempted to unify the four known forces of nature. Time runs to the right.

1.2.3 The cosmic uroborus

Taken together, scientific progress on both the outer and inner fronts can certainly be regarded as a triumph. In particular, physics has revealed a unity about the Universe which makes it clear that everything is connected in a way which would have seemed inconceivable a few decades ago. This unity is succinctly encapsulated in the image of the uroborus (i.e. the snake eating its own tail). This is shown in Fig. 1.2 (adapted from a picture originally presented by Sheldon Glashow) and demonstrates the intimate link between the macroscopic domain (on the left) and the microscopic domain (on the right).

The pictures drawn around the snake represent the different types of structure which exist in the Universe. Near the bottom are human beings. As we move to the left, we encounter successively larger objects: a mountain, a planet, a star, the solar system, a galaxy, a cluster of galaxies and finally the entire observable Universe. As we move to the right, we encounter successively smaller objects: a cell, a DNA molecule, an atom, a nucleus, a quark, the GUT scale and finally the Planck length. The numbers at the edge indicate the scale of these structures in centimetres. As one moves clockwise from the tail to the head, the scale increases through 60 decades: from the smallest meaningful scale allowed by quantum gravity (10^{-33} cm) to the scale of the visible Universe (10^{27} cm). If one expresses these scales in units of the Planck length, they go from 0 to 60, so the uroborus provides a sort of ‘clock’ in which each ‘minute’ corresponds to a factor of 10 in scale.



A further aspect of the uroborus is indicated by the horizontal lines. These correspond to the four interactions and illustrate the subtle connection between microphysics and macrophysics. For example, the ‘electric’ line connects an atom to a planet because the structure of a solid object is determined by atomic and intermolecular forces, both of which are electrical in origin. The ‘strong’ and ‘weak’ lines connect a nucleus to a star because the strong force, which holds nuclei together, also provides the energy released in the nuclear reactions which power a star, and the weak force, which causes nuclei to decay, also prevents stars from burning out too soon. The ‘GUT’ line connects the grand unification scale with galaxies and clusters because the density fluctuations which led to these objects originated when the temperature of the Universe was high enough for GUT

interactions to be important. Indeed the Big Bang theory suggests that these features arose when the current observable Universe had the size of a grapefruit!

The significance of the head meeting the tail is that the entire Universe was once compressed to a point of infinite density (or, more strictly, the Planck density). Since light travels at a finite speed, we can never see further than the distance light has travelled since the Big Bang, about 10^{10} light-years; more powerful telescopes merely probe to earlier times. Cosmologists now have a fairly complete picture of the history of the Universe: as one goes back in time, galaxy formation occurred at a billion years after the Big Bang, the background radiation last interacted with matter at a million years, the Universe's energy was dominated by its radiation content before about 10 000 years, light elements were generated through cosmological nucleosynthesis at around 3 minutes, antimatter was abundant before about a microsecond (before which there was just a tiny excess of matter over antimatter), electroweak unification occurred at a billionth of a second (the highest energy which can be probed experimentally), grand unification and inflation occurred at 10^{-35} s and the quantum gravity era (the smallest meaningful time) was at 10^{-43} s.

Perhaps the most striking aspect of the top of the uroborus is its link with higher dimensions. On the microscopic side, this arises because the various versions of superstring theory all suppose that the Universe has more than the three dimensions of space which we actually observe but with the extra dimensions being compactified. On the macroscopic side, the higher-dimensional link arises because we have seen that some versions of M-theory suggest that the Universe could be a 4-dimensional 'brane' in a higher-dimensional 'bulk' [17, 18]. This suggests that there might be many other branes in the bulk, although we have seen there are multiverse proposals which do not involve extra dimensions.

Figure 1.2 also has an historical aspect, since it shows how humans have systematically expanded the outermost and innermost limits of his awareness. Thus primitive humans were aware of scales from about 10^{-2} cm (mites) to 10^7 cm (mountains); eighteenth century humans were aware of scales from about 10^{-5} cm (bacteria) to 10^{17} cm (the solar system); and twentieth-century humans were aware of scales from about 10^{-13} cm (atomic nuclei) to 10^{27} cm (the most distant galaxies). Indeed it is striking that science has already expanded the macroscopic frontier as far as possible, although experimentally we may never get much below the electroweak scale in the microscopic direction. We might therefore regard the uroborus as representing the blossoming of human consciousness.

1.3 But is the multiverse science?

Despite the growing popularity of the multiverse proposal, it must be admitted that many physicists remain deeply uncomfortable with it. The reason is clear: the idea is highly speculative and, from both a cosmological and a particle physics perspective, the reality of a multiverse is currently untestable. Indeed, it may always remain so, in the sense that astronomers may never be able to observe the other universes with telescopes and particle physicists may never be able to observe the extra dimensions with their accelerators. The only way out would be if the effects of extra dimensions became ‘visible’ at the TeV scale, in which case they might be detected when the Large Hadron Collider becomes operational in 2007. This would only be possible if the extra dimensions were as large as a millimetre. However, it would be very fortunate (almost anthropically so) if the scale of quantum gravity just happened to coincide with the largest currently accessible energy scale.

For these reasons, some physicists do not regard these ideas as coming under the purview of science at all. Since our confidence in them is based on faith and aesthetic considerations (for example mathematical beauty) rather than experimental data, they regard them as having more in common with religion than science. This view has been expressed forcefully by commentators such as Sheldon Glashow [22], Martin Gardner [23] and George Ellis [24], with widely differing metaphysical outlooks. Indeed, Paul Davies [25] regards the concept of a multiverse as just as metaphysical as that of a Creator who fine-tuned a single universe for our existence. At the very least the notion of the multiverse requires us to extend our idea of what constitutes legitimate science.

In some people’s eyes, of course, cosmology has always bordered on metaphysics. It has constantly had to battle to prove its scientific respectability, fighting not only the religious, but also the scientific orthodoxy. For example, the prevalent view until well into the nineteenth century (long after the demise of the heliocentric picture) was that speculations about things beyond the Solar System was not proper science. This was reflected by Auguste Comte’s comments on the study of stars in 1859 [26]:

Never, by any means, will we be able to study their chemical compositions. The field of positive philosophy lies entirely within the Solar System, the study of the Universe being inaccessible in any possible science.

However, Comte had not foreseen the advent of spectroscopy, triggered by Gustav Kirchhoff’s realization in the same year that the dark lines in the solar spectrum were absorption features associated with chemical elements.

For the first time this allowed astronomers to probe the composition of distant stars.

Cosmology attained the status of a proper science in 1915, when the advent of general relativity gave the subject a secure mathematical basis. The discovery of the cosmological expansion in the 1920s then gave it a firm empirical foundation. Nevertheless, it was many decades before it gained full scientific recognition. For example, when Ralph Alpher and Robert Herman were working on cosmological nucleosynthesis in the 1940s, they recall [27]: ‘Cosmology was then a sceptically regarded discipline, not worked in by sensible scientists.’ Only with the detection of the microwave background radiation in 1965 was the hot Big Bang theory established as a branch of mainstream physics, and only with the recent results from the WMAP satellite (postdating the Stanford meeting which led to this book) has it become a *quantitative* science with real predictive power.

Nevertheless, cosmology is still different from most other branches of science; one cannot experiment with the Universe, and speculations about processes at very early and very late times depend upon theories of physics which may never be directly testable. Because of this, more conservative physicists still tend to regard cosmological speculations as going beyond the domain of science. The introduction of anthropic reasoning doubtless enhanced this view. On the other hand, other physicists have always held a more positive opinion, so there has developed a polarization of attitudes towards the anthropic principle. This is illustrated by the following quotes. The first is from the protagonist Freeman Dyson [28]:

I do not feel like an alien in this Universe. The more I examine the Universe and examine the details of its architecture, the more evidence I find that the Universe in some sense must have known we were coming.

This might be contrasted with the view of the antagonist Heinz Pagels [29]:

The influence of the anthropic principle on contemporary cosmological models has been sterile. It has explained nothing and it has even had a negative influence. I would opt for rejecting the anthropic principle as needless clutter in the conceptual repertoire of science.

An intermediate stance is taken by Brandon Carter [2], who might be regarded as one of the fathers of the anthropic principle:

The anthropic principle is a middle ground between the primitive anthropocentrism of the pre-Copernican age and the equally unjustifiable antithesis that no place or time in the Universe can be privileged in any way.

The growing popularity of the multiverse picture has encouraged a drift towards Carter's view, because it suggests that the anthropic fine-tunings can at least have a 'quasi-physical' explanation. To the hard-line physicist, the multiverse may not be entirely respectable, but it is at least preferable to invoking a Creator. Indeed anthropically inclined physicists like Susskind and Weinberg are attracted to the multiverse precisely because it seems to dispense with God as the explanation of cosmic design.²

In fact, the dichotomy in attributing anthropic fine-tunings to God or the multiverse is too simplistic. While the fine-tunings certainly do not provide unequivocal evidence for God, nor would the existence of a multiverse preclude God since – as emphasized by Robin Collins [30] – there is no reason why a Creator should not act through the multiverse. Nevertheless, the multiverse proposal certainly poses a serious challenge to the theological view, so it is not surprising that it has commended itself to atheists. Indeed, Neil Manson has described the multiverse as 'the last resort for the desperate atheist' [31].

By emphasizing the scientific legitimacy of anthropic and multiverse reasoning, I do not intend to deny the relevance of these issues to the science–religion debate [32]. The existence of a multiverse would have obvious religious implications [33], so contributions from theologians are important. More generally, cosmology addresses fundamental questions about the origin of matter and mind, which are clearly relevant to religion, so theologians need to be aware of the answers it provides. Of course, the remit of religion goes well beyond the materialistic issues which are the focus of cosmology. Nevertheless, in so much as religious and cosmological truths overlap, they must be compatible. This has been stressed by Ellis [34], who distinguishes between Cosmology (with a big C) – which takes into account 'the magnificent gestures of humanity' – and cosmology (with a small c), which just focuses on physical aspects of the Universe. In his view, morality is embedded in the cosmos in some fundamental way. Similar ideas have been expounded by John Leslie [35].

On the other hand, science itself cannot deal with such issues, and it seems unlikely that – even in the extended form required to accommodate the multiverse – science will ever prove or disprove the existence of God. Some people may see in the physical world some hint of the divine, but this can only provide what John Polkinghorne describes as 'nudge' factors [36].

² It should be cautioned that the concept of 'cosmic design' being described here has nothing to do with the 'Intelligent Design' movement in the USA. Nevertheless, atheists might hope that the multiverse theory will have the same impact in the context of cosmic design as the theory of evolution did in the context of biological design.

Convictions about God's existence must surely come from 'inside' rather than 'outside' and even those eminent physicists who are mystically inclined do not usually base their faith on scientific revelations [37]. For this reason, theology receives rather short shrift in this volume. The contributors are nearly all physicists, and even those of a theological disposition have generally restricted their remarks to scientific considerations.

1.4 Overview of book

Part I contains articles deriving from two talks at the symposium *Expectations of a Final Theory*, which was held in Cambridge in September 2005. These provide appropriate opening chapters for this volume because of their historical perspective and because they illustrate the way in which the subject has been propelled by a combination of developments in cosmology and particle physics. Starting with contributions from two Nobel laureates also serves to emphasize the degree of respectability that the topic has now attained!

In the first contribution, 'Living in the multiverse', based on his opening talk at the Cambridge meeting, Steven Weinberg argues that the idea of the multiverse represents an important change in the nature of science, a radical shift in what we regard as legitimate physics. This shift is prompted by a combination of developments on the theoretical and the observational fronts. In particular, he highlights the anthropic constraint on the value of the vacuum energy or cosmological constant, a constraint which he himself first pointed out in 1987 and might be regarded as one of the few successful anthropic predictions. He also highlights the string landscape scenario, which is perhaps the most plausible theoretical basis for the multiverse proposal and is the focus of several later chapters.

Frank Wilczek's contribution, aptly entitled 'Enlightenment, knowledge, ignorance, temptation', is based on his summary talk at the Cambridge meeting. In this, he discusses the historical and conceptual roots of reasoning about the parameters of fundamental physics and cosmology based on selection effects. He describes the developments which have improved the status of such reasoning, emphasizing that these go back well before string theory. He is well aware of the downside of this development, but accepts it as part of the price that has to be paid. Such reasoning can and should be combined with arguments based on symmetry and dynamics; it supplements them, but does not replace them. This view is cogently encapsulated in Wilczek's eponymous classification of physical parameters.

1.4.1 *Cosmology and astrophysics*

Part II contains chapters whose emphasis is primarily on cosmology and astrophysics. The opening chapter, ‘Cosmology and the multiverse’, is by Martin Rees, one of the foremost champions of the multiverse concept and the host of the two Cambridge meetings represented in this volume. He points out that the parts of space and time that are directly observable (even in principle) may be an infinitesimal part of physical reality. Rejecting the unobservable part as a suitable subject for scientific discourse at the outset is unjustified because there is a blurred transition – what he describes as a ‘slippery slope’ – between what is observable and unobservable. After briefly addressing some conceptual issues, he discusses what the Universe would be like if some of the key cosmological numbers were different, and how one can in principle test specific hypotheses about the physics underlying the multiverse.

Although the focus of this volume is the multiverse rather than the anthropic principle, it is important to recall the fine-tunings which the multiverse proposal is purporting to explain. Indeed, in the absence of *direct* evidence for other universes, these might be regarded as providing the only *indirect* evidence. This motivates the inclusion of my own chapter, ‘The anthropic principle revisited’, in which I reconsider the status of some of the arguments presented in my 1979 *nature* paper with Rees [1]. Although I also veer into more philosophical issues, I have included my chapter here because most of the anthropic relationships are associated with cosmology and astrophysics. I emphasize that the key feature of the anthropic fine-tunings is that they seem necessary for the emergence of *complexity* during the evolution of the Universe from the Big Bang. The existence of conscious observers is just one particular manifestation of this and may not be fundamental.

In ‘Cosmology from the top down’, Stephen Hawking contrasts different approaches to the central questions of cosmology: why is the Universe spatially flat and expanding; why is it 4-dimensional; why did it start off with small density fluctuations; why does the Standard Model of particle physics apply? Some physicists would prefer to believe that string theory, or M-theory, will answer these questions and uniquely predict the features of the Universe. Others adopt the view that the initial state of the Universe is prescribed by an outside agency, code-named God, or that there are many universes, with ours being picked out by the anthropic principle. Hawking argues that string theory is unlikely to predict the distinctive features of the Universe. But neither is he an advocate of God. He therefore opts for

the last approach, favouring the type of multiverse which arises naturally within the context of his own work in quantum cosmology.

Several other contributors regard quantum cosmology as providing the most plausible conceptual framework for the multiverse, so the book returns to this theme later. However, the multiverse hypothesis comes in many different guises, and these are comprehensively summarized in Max Tegmark's chapter, 'The multiverse hierarchy'. Indeed, Tegmark argues that the key question is not *whether* parallel universes exist but on *how many* levels they exist. He shows that physical theories involving parallel universes form a four-level hierarchy, allowing progressively greater diversity. Level I is associated with inflation and contains Hubble volumes realizing all possible initial conditions. This is relatively uncontroversial, since it is a natural consequence of the cosmological 'concordance' model. Level II assumes that different regions of space can exhibit different effective laws of physics (i.e. different physical constants, different dimensionality and different particle content). For example, inflation models in the string landscape scenario subdivide into four increasingly diverse sublevels: IIa involves the same effective laws but different post-inflationary bubbles; IIb involves different minima in the effective supergravity potential; IIc involves different fluxes (of particular fields) for a given compactification; and IId involves different compactifications. Level III corresponds to the 'many worlds' of quantum theory. Tegmark argues that the other branches of the wave-function add nothing qualitatively new, even though historically this level has been the most controversial. Finally, Level IV invokes other mathematical structures, associated with different fundamental equations of physics. He then raises the question of how multiverse models can be falsified and argues that there is a severe 'measure problem' that must be solved to make testable predictions at levels II–IV. This point is addressed in more detail by later contributors.

Tegmark's classification emphasizes the central role of inflation, which postulates an era in the very early Universe when the expansion was accelerating. Inflation is invoked to explain two of the most striking features of the Universe – its smoothness and flatness – and to many physicists the theory still provides the most natural basis for the multiverse scenario. One of the prime advocates of the anthropic aspects of inflation is Andrei Linde, so it is most appropriate that he contributes the next chapter, 'The inflationary multiverse'. He first places the anthropic principle in an historical context: although anthropic considerations can help us understand many properties of our world, for a long time many scientists were ashamed to use the principle in their research because it seemed too metaphysical. However,

the ‘chaotic’ inflationary scenario – which Linde pioneered and describes here – provides a simple justification for it. He especially favours ‘eternal’ inflation and links this to developments in string theory. He then discusses the implications of this idea for dark energy, relic axions and electroweak symmetry-breaking. These implications are explored in more detail in several later chapters, but Linde’s article serves as an excellent introduction to these ideas and brings them all together.

One of the issues raised by Linde is the prevalence of dark matter, and this is the focus of the second contribution by Frank Wilczek, ‘A model of anthropic reasoning: the dark to ordinary matter ratio’. He focuses on a dark matter candidate called the axion, which is a particle associated with the breaking of Peccei–Quinn (i.e. strong CP) symmetry in the early Universe. Large values of the symmetry-breaking energy scale (associated with large values of the Peccei–Quinn ‘misalignment’ angle) are forbidden in conventional axion cosmology. However, if inflation occurs after the breaking of Peccei–Quinn symmetry, large values are permitted providing we inhabit a region of the multiverse where the initial misalignment is small. Although such regions may occupy only a small volume of the multiverse, they contain a large fraction of potential observers. This scenario therefore yields a possible anthropic explanation of the approximate equality of the dark matter and baryon densities.

We have seen that another striking feature of the Universe is that its expansion appears to be accelerating under the influence of some form of ‘dark energy’. The source of this energy is uncertain, but it may be associated with a cosmological constant. Indeed, we have seen that one of the most impressive successes of anthropic reasoning is that it may be able to explain the present value of the cosmological constant. Several contributions touch on this, but the most comprehensive treatment is provided by Alex Vilenkin, whose chapter, ‘Anthropic predictions: the case of the cosmological constant’, reviews the history and nature of this prediction. He also discusses the inclusion of other variable parameters (such as the neutrino mass) and the implications for particle physics. In anticipation of a theme which emerges later in the book, he emphasizes that anthropic models give testable predictions, which can be confirmed or falsified at a specified confidence level. However, anthropic predictions always have an intrinsic variance, which cannot be reduced indefinitely as theory and observations progress.

The cosmological constant also plays a central role in James Bjorken’s chapter, ‘The definition and classification of universes’. If the concept of a multiverse makes sense, one needs a specific, standardized definition for member universes which are similar to our own. Crucial to this description

is the definition of the ‘size’ of the universe and, for the de Sitter model, Bjorken takes this to be the asymptotic value of the inverse Hubble constant. This is directly related to the value of the cosmological constant, so this parameter plays a natural role in his classification. He further proposes that the vacuum parameters and coupling constants of the Standard Model in any universe are dependent upon this size. Anthropic considerations then limit the size of habitable universes (as we understand that concept) to be within a factor of 2 of our own. Implications of this picture for understanding the ‘hierarchy problem’ in the Standard Model are discussed, as are general issues of falsifiability and verifiability.

Bjorken does not attempt to provide a physical basis for models with different cosmological constants, but a possible motivation comes from string theory, or M-theory. This point is discussed by several contributors, but the most thorough discussion of the cosmological applications of the idea is provided in Renata Kallosh’s chapter, ‘M/string theory and anthropic reasoning’. Here she outlines some recent cosmological studies of M/string theory and gives a couple of examples where anthropic reasoning – combined with our current incomplete understanding of string theory and supergravity – helps to shed light on the mysterious properties of dark energy. This is a rather technical article, but it is very important because it describes the results of her famous paper with A. Linde, S. Kachru and S. Trivedi, which shows that M/string theory allows models with a positive cosmological constant. This was a crucial development because string theorists used to assume that the constant would have to be *negative*, so this is an example of how cosmology has led to important insights into particle physics.

Closely related to Kallosh’s theme is the final chapter in Part II by Savas Dimopoulos and Scott Thomas, ‘The anthropic principle, dark energy and the LHC’. Here they argue that – in a broad class of theories – anthropic reasoning leads to a time-dependent vacuum energy with distinctive and potentially observable characteristics. The most exciting aspect of this proposal is that it leads to predictions that might be testable with the Large Hadron Collider, due to start operating in 2007. This illustrates the intimate link between cosmology and particle physics, so this naturally leads into the next part of the volume, which focuses on particle physics aspects of the multiverse hypothesis.

1.4.2 Particle physics and quantum theory

Part III starts with two articles on the values of the constants of particle physics, then moves onto the link with string theory, and concludes with

articles concerned with quantum theory. There is a two-fold connection with quantum theory, since the ‘many worlds’ interpretation of quantum mechanics provided one of the earliest multiverse scenarios (i.e. Tegmark’s Level III) and quantum cosmology provides one of the latest.

That the multiverse wave-function can explore a multitude of vacua with different symmetries and parameters is the starting point of Craig Hogan’s chapter, ‘Quarks, electrons and atoms in closely related universes’. In the context of such models, he points out that properties of universes closely related to ours can be understood by examining the consequences of small departures of physical parameters from their observed values. The masses of the light fermions that make up the stable matter of which we comprise – the up and down quarks and the electron – have values in a narrow window that allows the existence of a variety of nuclei other than protons and also atoms with stable shells of electrons that are not devoured by their nuclei. Since a living world with molecules needs stable nuclei other than protons and neutrons, these fundamental parameters of the Standard Model are good candidates for quantities whose values are determined through selection effects within a multiverse. Hogan also emphasizes another possible link with observation. If the fermion masses are fixed by brane condensation or compactification of extra dimensions, there may be an observable fossil of this ‘branching event’ in the form of a gravitational-wave background.

In the second chapter, ‘The fine-tuning problems of particle physics and anthropic mechanisms’, John Donoghue emphasizes that many of the classic problems of particle physics appear in a very different light when viewed from the perspective of the multiverse. Parameters in particle physics are regarded as fine-tuned if the size of the quantum corrections to their values in perturbation theory is large compared with their ‘bare’ values. Three parameters in the Standard Model are particularly puzzling because they are unnaturally small. Two of these – the Higgs vacuum expectation value and the cosmological constant – constitute the two great fine-tuning problems that motivate the field. The third is the strong CP violating factor, already highlighted in Wilczek’s second contribution. All of these fine-tunings are alleviated when one accounts for the anthropic constraints which exist in a multiverse. However, the challenge is to construct a realistic physical theory of the multiverse and to test it. Donoghue describes some phenomenology of the quark and lepton masses that may provide a window on the multiverse theory.

The main reason that particle physicists have become interested in the multiverse proposal is the development in string theory. In particular, the possibility that M-theory may lead to a huge number of vacuum states – each

associated with a different universe – is a crucial feature of Leonard Susskind’s string landscape proposal. In ‘The anthropic landscape of string theory’, he makes some educated guesses about the landscape of string theory vacua and – based on the recent work of a number of authors – argues that the landscape could be unimaginably large and diverse. Whether we like it or not, this is the kind of behaviour that gives credence to the anthropic principle. He discusses the theoretical and conceptual issues that arise in a cosmology based on the diversity of environments implicit in string theory. Some of the later stages of his exposition are fairly technical, but these ideas are of fundamental importance to this volume. Indeed Susskind’s chapter has already been on the archives for several years and is one of the most cited papers in the field.

As already stressed, the ‘many worlds’ interpretation of quantum theory provided one of the earliest versions of the multiverse scenario, and this is particularly relevant to quantum cosmology, which is most naturally interpreted in terms of this proposal. This view is advocated very cogently in ‘Cosmology and the many worlds interpretation of quantum mechanics’ by Viatcheslav Mukhanov. Indeed, he argues that the wave-function of the Universe and the cosmological perturbations generated by inflation can *only* be understood within Everett’s interpretation of quantum mechanics. The main reason it has not been taken seriously by some physicists is that it predicts we each have many copies, which may seem unpalatable. However, Mukhanov argues that these copies are not ‘dangerous’ because we cannot communicate with them.

The link with quantum cosmology is probed further by James Hartle in ‘Anthropic reasoning and quantum cosmology’. He stresses that anthropic reasoning requires a theory of the dynamics and quantum initial condition of the Universe. Any prediction in quantum cosmology requires both of these. But conditioned on this information alone, we expect only a few general features of the Universe to be predicted with probabilities near unity. Most useful predictions are of conditional probabilities that assume additional information beyond the dynamics and quantum state. Anthropic reasoning utilizes probabilities conditioned on our existence. Hartle discusses the utility, limitations and theoretical uncertainty involved in using such probabilities, as well as the predictions resulting from various levels of ignorance of the quantum state.

The link between Everett’s picture and the multiverse proposal is explored in depth by Brandon Carter. His chapter, ‘Micro-anthropic principle for quantum theory’, is somewhat technical but very valuable since it provides an excellent historical perspective and leads to an interpretation of the many

worlds picture which goes beyond the original Everett version. Probabilistic models, developed by workers such as Boltzmann on foundations due to pioneers such as Bayes, were commonly regarded as approximations to a deterministic reality before the roles were reversed by the quantum revolution under the leadership of Heisenberg and Dirac. Thereafter, it was the deterministic description that was reduced to the status of an approximation, with the role of the observer becoming particularly prominent. In Carter's view, the lack of objectivity in the original Copenhagen interpretation has not been satisfactorily resolved in newer approaches of the kind pioneered by Everett. The deficiency of such interpretations is attributable to their failure to allow for the anthropic aspect of the problem, in the sense that there is *a priori* uncertainty about the identity of the observer. Carter reconciles subjectivity with objectivity by distinguishing the concept of an *observer* from that of a *perceptor*, whose chances of identification with a particular observer need to be prescribed by a suitable anthropic principle. It is proposed that this should be done by an entropy ansatz, according to which the relevant micro-anthropic weighting is taken to be proportional to the logarithm of the relevant number of Everett-type branches.

1.4.3 *More general or philosophical aspects*

The final part of the book addresses more philosophical and epistemological aspects of the multiverse proposal – especially the issue of its scientific legitimacy. The chapters in this part are also written from a different standpoint from those in the earlier parts. Whereas the contributors in Parts I–III are mainly positive about the idea of the multiverse (otherwise they would presumably not be exploring it), some of the contributors in Part IV are rather critical – either preferring more theological interpretations of the anthropic coincidences or regarding multiverse speculations as going beyond science altogether.

The most sceptical of the critics is Lee Smolin. His chapter, 'Scientific alternatives to the anthropic principle', is the longest contribution in the volume and plays a crucial role in bringing all the criticisms of the multiverse proposal together. He first argues that the anthropic principle cannot be considered a part of science because it does not yield any falsifiable predictions. Claimed successful predictions are either uncontroversial applications of selection principles in one universe or they depend only on observed facts which are logically independent of any assumption about life or intelligence. The Principle of Mediocrity (first formulated by Vilenkin) is also examined and claimed to be unreliable, as arguments for true conclusions

can easily be modified to lead to false conclusions by reasonable changes in the specification of the ensemble in which we are assumed to be typical. However, Smolin shows that it is still possible to make falsifiable predictions from multiverse theories if the ensemble predicted has certain specified properties and he emphasizes his own favoured multiverse proposal – Cosmological Natural Selection – which involves the generation of descendant universes through black hole formation. This proposal remains unfalsified, but it is very vulnerable to falsification, which shows that it is a proper scientific theory. The consequences for recent applications of the anthropic principle in the context of string theory (as described in Part III) are also discussed.

Several other contributions in this part address the question of whether the multiverse proposal is scientifically respectable, although they do not all share Smolin's negative conclusion. In 'Making predictions in a multiverse: conundrums, dangers, coincidences', Anthony Aguirre accepts that the notion of many universes with different properties is one answer to the question of why the Universe is so hospitable to life. He also acknowledges that this notion naturally follows from current ideas in eternal inflation and M/string theory. But how do we test a multiverse theory and which of the many universes do we compare to our own? His chapter enumerates what would seem to be essential ingredients for making testable predictions, outlines different strategies one might take within this framework, and then discusses some of the difficulties and dangers inherent in these approaches. Finally, he addresses the issue of whether the predictions of multiverse theories share any general, qualitative features.

The issue of testing also features in the contribution of George Ellis, 'Multiverses: description, uniqueness and testing', who concludes that the multiverse proposal is not really proper science. He emphasizes that a multiverse is determined by specifying first a possibility space of potentially existing universes and then a distribution function on this space for actually existing universes. Ellis is sceptical because there is a lack of uniqueness at both these stages and we are unable either to determine observationally the specific nature of any multiverse that is claimed to exist or to validate experimentally any claimed causal mechanism that will create one. Multiverses may be useful in explanatory terms, but arguments for their existence are ultimately of a philosophical nature. Ellis is not against metaphysics – indeed he has written extensively on philosophical and theological issues – but he feels it should not be confused with science.

The importance of testing is also explored by Don Page in 'Predictions and tests of multiverse theories'. Page is also of a religious persuasion, but

he comes to a somewhat different conclusion from Ellis. A multiverse usually includes parts unobservable to us, but if the theory for it includes suitable measures for observations, what is observable can be explained by the theory even if it contains unobservable elements. Thus good multiverse theories *can* be tested. For Bayesian comparisons of different theories that predict more than one observation, Page introduces the concept of ‘typicality’ as the likelihood given by a theory that a random result of an observation would be at least as extreme as the result of one’s actual observation. He also links this to the interpretations of the quantum theory. Some multiverse theories can be regarded as pertaining to a *single* quantum state. This obeys certain equations, which raises the question of why those equations apply. Other theories can be regarded as pertaining to more than one quantum state, and these raise another question: why is the measure for the set of different universes such as to make our observations not too atypical?

The importance of a good probabilistic basis for assessing multiverse scenarios is also highlighted by Nick Bostrom’s chapter, ‘Observation selection theory and cosmological fine-tuning’. His title refers to a methodological tool for dealing with observation selection effects. Such a tool is necessary if observational consequences are to be derived from cosmological theory. It also has applications in other domains, such as evolution theory, game theory and the foundations of quantum mechanics. Bostrom shows that observation selection theory needs a probabilistic anthropic principle, which can be formalized in what he terms the ‘Observation Equation’. Some implications of this for the problem of cosmological fine-tuning are discussed.

The next two contributions tackle the religious issue explicitly. ‘Are anthropic arguments, involving multiverses and beyond, legitimate?’ is particularly welcome because it comes from William Stoeger, who is both a working scientist and a Jesuit priest. After reviewing the history of the anthropic principle, he discusses the two main versions of the strong form – a divine creator or a multiverse. The latter strives to confine anthropic arguments within the realms of science and invokes an actually existing ensemble of universes or universe domains. He critically examines the scientific status of this proposal, briefly indicating what is needed for the definition and testability of a multiverse, and then describes some purely scientific applications of anthropic arguments. After discussing the key philosophical presumption on which the strong anthropic principle rests – that the Universe could have been different – and its relationship to a possible final theory, he summarizes his main conclusions concerning the two ‘transcendent’ explanations of the strong anthropic principle. Even if a multiverse is proved to exist, Stoeger would not regard this as providing an *ultimate* explanation and it would

certainly not exclude the existence of God. However, he cautions that such considerations go beyond science itself.

As suggested by its title, the chapter by Robin Collins, ‘The multiverse hypothesis: a theistic perspective’, also takes an explicitly theological stance. Many people have promoted the multiverse hypothesis as the atheistic alternative to a theistic explanation of the fine-tuning of the cosmos for the existence of life. However, Collins argues that the multiverse hypothesis is also compatible with theism – indeed he claims that the generation of many universes by some physical process fits in well with the traditional belief that God is infinitely creative. Since such a process would have to be structured in just the right way to produce even one life-sustaining universe, this version of the multiverse hypothesis does not completely avoid the suggestion of design. Finally, he considers other pointers to a theistic explanation of the Universe, such as the beauty and elegance of the laws of nature, and argues that Tegmark’s multiverse hypothesis – that all possible laws of nature are actualized in some universe or another – does not adequately account for this aspect of the laws of nature.

There are, of course, alternative interpretations of the multiverse hypothesis which are neither anthropic nor theistic. One example of this is Smolin’s Cosmological Natural Selection proposal. Another (more exotic) version – which has been explored by Bostrom (though not in this volume) – is that the Universe is a computer simulation. This is the theme of John Barrow’s chapter, ‘Living in a simulated universe’. He explains why, if we live in a simulated reality, we might expect to see occasional glitches and small drifts in the supposed constants and laws of nature over time. There may even be evidence for this from astronomical observations, although the interpretation of these remains controversial.

Another possible interpretation of the anthropic tunings is provided in the final chapter, ‘Universes galore: where will it all end?’, by Paul Davies, who is also somewhat sceptical of the multiverse proposal. He argues that, although ‘a little bit of multiverse is good for you’, invoking multiverse explanations willy-nilly is a seductive slippery slope. Followed to its logical extreme, it leads to conclusions that are at best bizarre, at worst absurd. After reviewing several shortcomings of indiscriminate multiverse explanations, including the simulated multiverse discussed by Barrow, he challenges the false dichotomy that fine-tuning requires the existence of either a multiverse or some sort of traditional cosmic architect. Instead, he explores the possibility of a ‘third way’, involving a radical reappraisal of the notion of physical law, and presents a toy illustration from the theory of cellular automata.

References

- [1] B. J. Carr and M. J. Rees. *Nature*, **278** (1979), 605.
- [2] B. Carter. In *Confrontation of Cosmological Theory with Observational Data*, ed. M. S. Longair (Dordrecht: Reidel, 1974), pp. 291–298.
- [3] R. C. Tolman. *Relativity, Thermodynamics and Cosmology* (Oxford: Clarendon Press, 1934).
- [4] A. H. Guth. *Phys. Rev. D* **23** (1981), 347.
- [5] A. D. Linde. *Phys. Lett. B* **175** (1986), 395.
- [6] A. Vilenkin. *Phys. Rev. D* **27** (1983), 2848.
- [7] J. B. Hartle and S. W. Hawking. *Phys. Rev. D* **28** (1983), 2960.
- [8] S. W. Hawking and T. Hertog. *Phys. Rev. D* **73** (2006), 123527.
- [9] H. Everett. *Rev. Mod. Phys.* **29** (1957), 454.
- [10] D. Deutsch. *The Fabric of Reality* (London: Penguin, 1998).
- [11] M. Tegmark, In *Science and Ultimate Reality: From Quantum to Cosmos*, eds. J. D. Barrow, P. C. W. Davies & C. L. Harper (Cambridge: Cambridge University Press, 2003), p. 459.
- [12] G. L. Kane, M. J. Perry and A. N. Zytlow. *New Astron.* **7** (2002), 45.
- [13] R. Bousso and J. Polchinski. *JHEP*, **06** (2000), 006.
- [14] L. Susskind. This volume (2007).
- [15] S. Weinberg. *Phys. Rev. Lett.* **59** (1987), 2607.
- [16] S. Weinberg. *Rev. Mod. Phys.* **61** (1989), 1.
- [17] L. Randall and R. Sundrum. *Phys. Rev. Lett.* **83** (1999), 4690.
- [18] L. Randall. *Warped Passages: Unravelling the Universe's Hidden Dimensions* (London: Penguin, 2005).
- [19] S. Kachru, R. Kallosh, A. Linde and S. R. Trivedi. *Phys. Rev. D* **68** (2003), 046005.
- [20] J. Khoury, B. A. Ovrut, P. J. Steinhardt and N. Turok. *Phys. Rev. D* **64** (2001), 123522.
- [21] A. R. Liddle and L. A. Urena-Lopez. *Phys. Rev. Lett.* **97** (2006), 161301.
- [22] G. Brumfiel. *Nature*, **439** (2006), 10.
- [23] M. Gardner. *Are Universes Thicker than Blackberries?* (New York: W. W. Norton & Co. Ltd, 2003).
- [24] G. F. R. Ellis. This volume (2007).
- [25] P. C. W. Davies. This volume (2007).
- [26] A. Comte. *Cours de Philosophie Positive* (Paris: Bachelier, 1842).
- [27] R. A. Alpher and R. Herman. *Phys. Today*, **41** (1988), 24.
- [28] F. Dyson. *Rev. Mod. Phys.* **51** (1979), 447.
- [29] H. R. Pagels. *Perfect Symmetry* (New York: Simon & Schuster), p. 359.
- [30] R. Collins. This volume (2007).
- [31] N. A. Manson. *God and Design* (London: Routledge, 2003).
- [32] B. J. Carr. In *The Oxford Handbook of Religion and Science*, eds. P. Clayton and Z. Simpson (Oxford: Oxford University Press, 2006), p. 139.
- [33] R. Holder. *God, the Multiverse and Everything: Modern Cosmology and the Argument from Design* (Aldershot: Ashgate, 2004).
- [34] G. F. R. Ellis. *Before the Beginning: Cosmology Explained* (London: Boyars/Bowerdean, 1993).
- [35] J. Leslie. *Universes* (London: Routledge, 1989).
- [36] J. Polkinghorne. *The Faith of a Physicist* (Princeton, NJ: Princeton University Press, 1994).
- [37] K. Wilbur. *Quantum Questions: Mystical Writings of the Worlds Greatest Physicists* (Boston: Shambhala, 2001).

2

Living in the multiverse

Steven Weinberg

Physics Department, University of Texas at Austin

Opening talk at the symposium *Expectations of a Final Theory* at
Trinity College, Cambridge, 2 September 2005

2.1 Introduction

We usually mark advances in the history of science by what we learn about nature, but at certain critical moments the most important thing is what we discover about science itself. These discoveries lead to changes in how we score our work, in what we consider to be an acceptable theory.

For an example, look back to a discovery made just one hundred years ago. Before 1905 there had been numerous unsuccessful efforts to detect changes in the speed of light, due to the motion of the Earth through the ether. Attempts were made by Fitzgerald, Lorentz and others to construct a mathematical model of the electron (which was then conceived to be the chief constituent of all matter) that would explain how rulers contract when moving through the ether in just the right way to keep the apparent speed of light unchanged. Einstein instead offered a symmetry principle, which stated that not just the speed of light, but all the laws of nature are unaffected by a transformation to a frame of reference in uniform motion. Lorentz grumbled that Einstein was simply assuming what he and others had been trying to prove. But history was on Einstein's side. The 1905 Special Theory of Relativity was the beginning of a general acceptance of symmetry principles as a valid basis for physical theories.

This was how Special Relativity made a change in science itself. From one point of view, Special Relativity was no big thing – it just amounted to the replacement of one 10-parameter spacetime symmetry group, the Galileo group, with another 10-parameter group, the Lorentz group. But never

before had a symmetry principle been taken as a legitimate hypothesis on which to base a physical theory.

As usually happens with this sort of revolution, Einstein's advance came with a retreat in another direction: the effort to construct a classical model of the electron was permanently abandoned. Instead, symmetry principles increasingly became the dominant foundation for physical theories. This tendency was accelerated after the advent of quantum mechanics in the 1920s, because the survival of symmetry principles in quantum theories imposes highly restrictive consistency conditions (existence of antiparticles, connection between spin and statistics, cancellation of infinities and anomalies) on physically acceptable theories. Our present Standard Model of elementary particle interactions can be regarded as simply the consequence of certain gauge symmetries and the associated quantum mechanical consistency conditions.

The development of the Standard Model did not involve any changes in our conception of what was acceptable as a basis for physical theories. Indeed, the Standard Model can be regarded as just quantum electrodynamics writ large. Similarly, when the effort to extend the Standard Model to include gravity led to widespread interest in string theory, we expected to score the success or failure of this theory in the same way as for the Standard Model: string theory would be a success if its symmetry principles and consistency conditions led to a successful prediction of the free parameters of the Standard Model.

Now we may be at a new turning point, a radical change in what we accept as a legitimate foundation for a physical theory. The current excitement is, of course, a consequence of the discovery of a vast number of solutions of string theory, beginning in 2000 with the work of Bousso and Polchinski [1].¹ The compactified six dimensions in Type II string theories typically have a large number (tens or hundreds) of topological fixtures (3-cycles), each of which can be threaded by a variety of fluxes. The logarithm of the number of allowed sets of values of these fluxes is proportional to the number of topological fixtures. Further, for each set of fluxes one obtains a different effective field theory for the modular parameters that describe the compactified 6-manifold, and for each effective field theory the number of local minima of the potential for these parameters is again proportional to

¹ Smolin [2] had noted earlier that string theory has a large number of vacuum solutions, and explored an imaginative possible consequence of this multiplicity. Even earlier, in the 1980s, Duff, Nilsson and Pope had noted that $D = 11$ supergravity has an infinite number of possible compactifications, but of course it was not then known that this theory is a version of string theory. For a summary, see ref. [3].

the number of topological fixtures. Each local minimum corresponds to the vacuum of a possible stable or metastable universe.

Subsequent work by Giddings, Kachru, Kallosh, Linde, Maloney, Polchinski, Silverstein, Strominger and Trivedi (in various combinations) [4–6] established the existence of a large number of vacua with positive energy densities. Ashok and Douglas [7] estimated the number of these vacua to be of order 10^{100} to 10^{500} . String theorists have picked up the term ‘string landscape’ for this multiplicity of solutions from Susskind [8], who took the term from biochemistry, where the possible choices of orientation of each chemical bond in large molecules lead to a vast number of possible configurations. Unless one can find a reason to reject all but a few of the string theory vacua, we may have to accept that much of what we had hoped to calculate are environmental parameters, like the distance of the Earth from the Sun, whose values we will never be able to deduce from first principles.

We lose some and win some. The larger the number of possible values of physical parameters provided by the string landscape, the more string theory legitimates anthropic reasoning as a new basis for physical theories. Any scientists who study nature must live in a part of the landscape where physical parameters take values suitable for the appearance of life and its evolution into scientists.

An apparently successful example of anthropic reasoning was already at hand by the time the string landscape was discovered. For decades there seemed to be something peculiar about the value of the vacuum energy density ρ_V . Quantum fluctuations in known fields at well understood energies (say, less than 100 GeV) give a value of ρ_V larger than observationally allowed by a factor 10^{56} . This contribution to the vacuum energy might be cancelled by quantum fluctuations of higher energy, or by simply including a suitable cosmological constant term in the Einstein field equations, but the cancellation would have to be exact to fifty-six decimal places. No symmetry argument or adjustment mechanism could be found that would explain such a cancellation. Even if such an explanation could be found, there would be no reason to suppose that the remaining net vacuum energy would be comparable to the *present* value of the matter density, and since it is certainly not very much larger, it was natural to suppose that it is very much less, too small to be detected.

On the other hand, if ρ_V takes a broad range of values in the multiverse, then it is natural for scientists to find themselves in a subuniverse in which ρ_V takes a value suitable for the appearance of scientists. I pointed out in 1987 that this value for ρ_V cannot be too large and positive, because then galaxies and stars would not form [9]. Roughly, this limit is that ρ_V should

be less than the mass density of the universe at the time when galaxies first condense. Since this was in the past, when the mass density was larger than at present, the anthropic upper limit on the vacuum energy density is larger than the present mass density, but not many orders of magnitude greater.

But anthropic arguments provide not just a bound on ρ_V , they give us some idea of the value to be expected: ρ_V should be not very different from the mean of the values suitable for life. This is what Vilenkin [10] calls the ‘Principle of Mediocrity’. This mean is positive, because if ρ_V were negative it would have to be less in absolute value than the mass density of the universe during the whole time that life evolves (otherwise the universe would collapse before any astronomers come on the scene [11]), while if ρ_V were positive, it would only have to be less than the mass density of the universe at the time when most galaxies form, giving a much broader range of possible positive than negative values. In 1997–98 Martel, Shapiro and I [12] carried out a detailed calculation of the probability distribution of values of ρ_V seen by astronomers throughout the multiverse, under the assumption that the *a priori* probability distribution is flat in the relatively very narrow range that is anthropically allowed (for earlier calculations, see refs. [13] and [14]). At that time, the value of the primordial root-mean-square (rms) fractional density fluctuation σ was not well known, since the value inferred from observations of the cosmic microwave background depended on what one assumed for ρ_V . It was therefore not possible to calculate a mean expected value of ρ_V , but for any assumed value of ρ_V we could estimate σ and use the result to calculate the fraction of astronomers that would observe a value of ρ_V as small as the assumed value. In this way, we concluded that if Ω_Λ (the dimensionless density parameter associated with ρ_V) turned out to be much less than 0.6, anthropic reasoning could not explain why it was so small. The editor of the *Astrophysical Journal* objected to publishing papers about anthropic calculations, and we had to sell our article by pointing out that we had provided a strong argument for abandoning an anthropic explanation of a small value of ρ_V if it turned out to be too small.

Of course, it turned out that ρ_V is not too small. Soon after this work, observations of type Ia supernovae revealed that the cosmic expansion is accelerating [15, 16] and gave the result that $\Omega_\Lambda \simeq 0.7$. In other words, the ratio of the vacuum energy density to the present mass density ρ_{M0} in *our* subuniverse (which I use just as a convenient measure of density) is about 2.3, a conclusion subsequently confirmed by observations of the microwave background [17].

This is still a bit low. Martel, Shapiro and I had found that the probability of a vacuum energy density this small was 12%. I have now recalculated the

probability distribution, using WMAP data and a better transfer function, with the result that the probability of a random astronomer seeing a value as small as $2.3\rho_{\text{M0}}$ is increased to 15.6%.² Now that we know σ , we can also calculate that the median vacuum energy density is $13.3\rho_{\text{M0}}$.

I should mention a complication in these calculations. The average of the product of density fluctuations at different points becomes infinite as these points approach each other, so the rms fractional density fluctuation σ is actually infinite. Fortunately, it is not σ itself that is really needed in these calculations, but the rms fractional density fluctuation averaged over a sphere of comoving radius R taken large enough so that the density fluctuation is able to hold on efficiently to the heavy elements produced in the first generation of stars. The results mentioned above were calculated for R (projected to the present) equal to 2 Mpc. These results are rather sensitive to the value of R ; for $R = 1$ Mpc, the probability of finding a vacuum energy as small as $2.3\rho_{\text{M0}}$ is only 7.2%. The estimate of the required value of R involves complicated astrophysics, and needs to be better understood.

2.2 Problems

Now I want to take up four problems we have to face in working out the anthropic implications of the string landscape.

What is the shape of the string landscape?

Douglas [18] and Dine and co-workers [19, 20] have taken the first steps in finding the statistical rules governing different string vacua. I cannot comment usefully on this, except to say that it would not hurt in this work if we knew what string theory is.

What constants scan?

Anthropic reasoning makes sense for a given constant if the range over which the constant varies in the landscape is large compared with the anthropically allowed range of values of the constant; for then it is reasonable to assume that the *a priori* probability distribution is flat in the anthropically allowed range. We need to know what constants actually ‘scan’ in this sense. Physicists would like to be able to calculate as much as possible, so we hope that not too many constants scan.

² This situation has improved since the release of the second and third year WMAP results. Assuming flat space, the ratio of the vacuum energy density to the matter density is now found to be about 3.2 rather than 2.3.

The most optimistic hypothesis is that the only constants that scan are the few whose dimensionality is a positive power of mass: the vacuum energy and whatever scalar mass or masses set the scale of electroweak symmetry-breaking. With all other parameters of the Standard Model fixed, the scale of electroweak symmetry-breaking is bounded above by about 1.4 to 2.7 times its value in our subuniverse, by the condition that the pion mass should be small enough to make the nuclear force strong enough to keep the deuteron stable against fission [21]. (The condition that the deuteron be stable against beta decay, which yields a tighter bound, does not seem to me to be necessary. Even a beta-unstable deuteron would live long enough to allow cosmological helium synthesis; helium would be burned to heavy elements in the first generation of very massive stars; and then subsequent generations could have long lifetimes burning hydrogen through the carbon cycle.) But the mere fact that the electroweak symmetry-breaking scale is only a few orders of magnitude larger than the QCD scale should not in itself lead us to conclude that it must be anthropically fixed. There is always the possibility that the electroweak symmetry-breaking scale is determined by the energy at which some gauge coupling constant becomes strong, and if that coupling happens to grow with decreasing energy a little faster than the QCD coupling, then the electroweak breaking scale will naturally be a few orders of magnitude larger than the QCD scale.

If the electroweak symmetry-breaking scale is anthropically fixed, then we can give up the decades long search for a natural solution of the hierarchy problem. This is a very attractive prospect, because none of the ‘natural’ solutions that have been proposed, such as technicolor or low-energy supersymmetry, were ever free of difficulties. In particular, giving up low-energy supersymmetry can restore some of the most attractive features of the non-supersymmetric Standard Model: automatic conservation of baryon and lepton number in interactions up to dimension 5 and 4, respectively; natural conservation of flavors in neutral currents; and a small neutron electric dipole moment. Arkani-Hamed and Dimopoulos [22] and others [23–25] have even shown how it is possible to keep the good features of supersymmetry, such as a more accurate convergence of the $SU(3) \times SU(2) \times U(1)$ couplings to a single value, and the presence of candidates for dark matter, WIMPs. The idea of this ‘split supersymmetry’ is that, although supersymmetry is broken at some very high energy, the gauginos and higgsinos are kept light by a chiral symmetry. (An additional discrete symmetry is needed to prevent lepton-number violation in higgsino–lepton mixing, and to keep the lightest supersymmetric particle stable.) One of the nice things about split supersymmetry is that, unlike many of the things we talk about these days,

it makes predictions that can be checked when the LHC starts operation. One expects a single neutral Higgs with a mass in the range 120 to 165 GeV, possible winos and binos, but no squarks or sleptons, and a long-lived gluino. (Incidentally, a Stanford group [26] has recently used considerations of Big Bang nucleosynthesis to argue that a 1 TeV gluino must have a lifetime less than 100 seconds, indicating a supersymmetry breaking scale less than 10^{10} GeV. But I wonder whether, even if the gluino has a longer lifetime and decays after nucleosynthesis, the universe might not thereby be reheated above the temperature of helium dissociation, giving Big Bang nucleosynthesis a second chance to produce the observed helium abundance.)

What about the dimensionless Yukawa couplings of the Standard Model? If these couplings are very tightly constrained anthropically, then we might reasonably suspect that they take a wide range of values in the multiverse, so that anthropic considerations can have a chance to affect the values we observe. Hogan [27, 28] has analyzed the anthropic constraints on these couplings, with the electroweak symmetry-breaking scale and the sum of the u and d Yukawa couplings held fixed, to avoid complications due to the dependence of nuclear forces on the pion mass. He imposes the following conditions: (1) $m_d - m_u - m_e > 1.2 \text{ MeV}$, so that the early universe does not become all neutrons; (2) $m_d - m_u + m_e < 3.4 \text{ MeV}$, so that the pp reaction is exothermic; and (3) $m_e > 0$. With three conditions on the two parameters $m_u - m_d$ and m_e , he naturally finds these parameters are limited to a finite region, which turns out to be quite small. At first sight, this gives the impression that the quark and lepton Yukawa couplings are subject to stringent anthropic constraints, in which case we might infer that the Yukawa couplings probably scan.

I have two reservations about this conclusion. The first is that the pp reaction is not necessary for life. For one thing, the pep reaction $p + p + e^- \rightarrow d + \nu$ can keep stars burning hydrogen for a long time. For this, we do not need $m_d - m_u + m_e < 3.4 \text{ MeV}$, but only the weaker condition $m_d - m_u - m_e < 3.4 \text{ MeV}$. The three conditions then do not constrain $m_d - m_u$ and m_e separately to any finite region, but only constrain the single parameter $m_d - m_u - m_e$ to lie between 1.2 MeV and 3.4 MeV, not a very tight anthropic constraint. (In fact, He^4 will be stable as long as $m_d - m_u - m_e$ is less than about 13 MeV, so stellar nucleosynthesis can begin with helium burning in the heavy stars of Population III, followed by hydrogen burning in later generations of stars.) My second reservation is that the anthropic constraints on the Yukawa couplings are alleviated if we suppose (as discussed above) that the electroweak symmetry-breaking scale is not fixed, but free to take whatever value is anthropically necessary. For instance,

according to the results of ref. [21], the deuteron binding energy could be made as large as about 3.5 MeV by taking the electroweak breaking scale much less than it is in our universe, in which case even the condition that the pp reaction be exothermic becomes much looser.

Incidentally, I do not set much store by the famous ‘coincidence’, emphasized by Hoyle, that there is an excited state of C^{12} with just the right energy to allow carbon production via α -Be⁸ reactions in stars. We know that even-even nuclei have states that are well described as composites of α -particles. One such state is the ground state of Be⁸, which is unstable against fission into two α -particles. The same α - α potential that produces that sort of unstable state in Be⁸ could naturally be expected to produce an unstable state in C^{12} that is essentially a composite of three α -particles, and that therefore appears as a low-energy resonance in α -Be⁸ reactions. So the existence of this state does not seem to me to provide any evidence of fine tuning.

What else scans? Tegmark and Rees [29] have raised the question of whether the rms density fluctuation σ may itself scan. If it does, then the anthropic constraint on the vacuum energy becomes weaker, resuscitating to some extent the problem of why ρ_V is so small. But Garriga and Vilenkin [30] have pointed out that it is really ρ_V/σ^3 that is constrained anthropically, so that, even if σ does scan, the anthropic prediction of this ratio remains robust.

Arkani-Hamed, Dimopoulos and Kachru [31], referred to below as ADK, have offered a possible reason for supposing that most constants do not scan. If there are a large number N of decoupled modular fields, each taking a few possible values, then the probability distribution of quantities that depend on all these fields will be sharply peaked, with a width proportional to $1/\sqrt{N}$. According to Distler and Varadarajan [32], it is not really necessary here to make arbitrary assumptions about the decoupling of the various scalar fields; it is enough to adopt the most general polynomial superpotential that is stable, in the sense that radiative corrections do not change the effective couplings for large N by amounts larger than the couplings themselves. Distler and Varadarajan emphasize cubic superpotentials, because polynomial superpotentials of order higher than cubic presumably make no physical sense. But it is not clear that even cubic superpotentials can be plausible approximations, or that peaks will occur at reasonable values in the distribution of dimensionless couplings rather than of some combinations of these couplings.³ It also is not clear that the multiplicity of vacua in this kind of effective scalar field theory can properly represent the multiplicity of flux values in string theories [33], but even if it cannot, it presumably can represent the variety of minima of the potential for a given set of flux vacua.

³ M. Douglas, private communication.

If most constants do not effectively scan, then why should anthropic arguments work for the vacuum energy and the electroweak breaking scale? ADK point out that, even if some constant has a relatively narrow distribution, anthropic arguments will still apply if the anthropically allowed range is even narrower and near a point around which the distribution is symmetric. (ADK suppose that this point would be at zero, but this is not necessary.) This is the case, for instance, for the vacuum energy if the superpotential W is the sum of the superpotentials W_n for a large number of decoupled scalar fields, for each of which there is a separate broken R symmetry, so that the possible values of each W_n are equal and opposite. The probability distribution of the total superpotential $W = \sum_{n=1}^N W_n$ will then be a Gaussian peaked at $W=0$ with a width proportional to $1/\sqrt{N}$, and the probability distribution of the supersymmetric vacuum energy $-8\pi G|W|^2$ will extend over a correspondingly narrow range of negative values, with a maximum at zero. When supersymmetry breaking is taken into account, the probability distribution widens to include positive values of the vacuum energy, extending out to a positive value depending on the scale of supersymmetry breaking. For any reasonable supersymmetry breaking scale, this probability distribution, though narrow compared with the Planck scale, will be very wide compared with the very narrow anthropically allowed range around $\rho_V=0$, so within this range the probability distribution can be expected to be flat, and anthropic arguments should work. Similar remarks apply to the μ -term of the supersymmetric Standard Model, which sets the scale of electroweak symmetry-breaking.

How should we calculate anthropically conditioned probabilities?

We would expect the anthropically conditioned probability distribution for a given value of any constant that scans to be proportional to the number of scientific civilizations that observe that value. In the calculations described above, Martel, Shapiro and I took this number to be proportional to the *fraction* of baryons that find themselves in galaxies, but what if the total number of baryons itself scans? What if it is infinite?

How is the landscape populated?

There are at least four ways in which we might imagine the different ‘universes’ described by the string landscape actually to exist.

- (i) The various subuniverses may be simply different regions of space. This is most simply realized in the chaotic inflation theory [34–38]. The scalar fields in different inflating patches may take different values, giving rise to different values for various effective coupling constants. Indeed, Linde speculated about the application of the

anthropic principle to cosmology soon after the proposal of chaotic inflation [39, 40].

- (ii) The subuniverses may be different eras of time in a single Big Bang. For instance, what appear to be constants of nature might actually depend on scalar fields that change very slowly as the universe expands [41].
- (iii) The subuniverses may be different regions of spacetime. This can happen if, instead of changing smoothly with time, various scalar fields on which the ‘constants’ of nature depend change in a sequence of first-order phase transitions [42–44]. In these transitions, metastable bubbles form within a region of higher vacuum energy; then within each bubble there form further bubbles of even lower vacuum energy; and so on. In recent years this idea has been revived in the context of the string landscape [45, 46]. In particular, it has been suggested [47] that in this scenario the curvature of our universe is small for anthropic reasons, and hence possibly large enough to be detected.
- (iv) The subuniverses could be different parts of quantum mechanical Hilbert space. In a reinterpretation of Hawking’s earlier work on the wave-function of the universe [48, 49],⁴ Coleman [51] showed that certain topological fixtures known as wormholes in the path integral for the Euclidean wave-function of the Universe would lead to a superposition of wave-functions in which any coupling constant not constrained by symmetry principles would take any possible value.⁵ Ooguri, Vafa and Verlinde [57] have argued for a particular wave-function of the universe, but it escapes me how anyone can tell whether this or any other proposed wave-function is *the* wave-function of the universe.

These alternatives are by no means mutually exclusive. In particular, it seems to me that, whatever one concludes about the first three alternatives, we will still have the possibility that the wave-function of the universe is a superposition of different terms representing different ways of populating the landscape in space and/or time.

⁴ Some of this work is based on an initial condition for the origin of the universe proposed by Hartle and Hawking [50].

⁵ It has been argued by Hawking and others that the wave-function of the universe is sharply peaked at values of the constants that yield a zero vacuum energy at late times [52–55]. This view has been challenged in ref. [56]. I am assuming here that there are no such peaks.

2.3 Conclusion

In closing, I would like to comment on the impact of anthropic reasoning within and beyond the physics community. Some physicists have expressed a strong distaste for anthropic arguments. (I have heard David Gross say ‘I hate it’.) This is understandable. Theories based on anthropic calculations certainly represent a retreat from what we had hoped for: the calculation of all fundamental parameters from first principles. It is too soon to give up on this hope, but without loving it we may just have to resign ourselves to a retreat, just as Newton had to give up Kepler’s hope of a calculation of the relative sizes of planetary orbits from first principles.

There is also a less creditable reason for hostility to the idea of a multiverse, based on the fact that we will never be able to observe any subuniverses except our own. Livio and Rees [58] and Tegmark [59] have given thorough discussions of various other ingredients of accepted theories that we will never be able to observe, without our being led to reject these theories. The test of a physical theory is not that everything in it should be observable and every prediction it makes should be testable, but rather that enough is observable and enough predictions are testable to give us confidence that the theory is right.

Finally, I have heard the objection that, in trying to explain why the laws of nature are so well suited for the appearance and evolution of life, anthropic arguments take on some of the flavour of religion. I think that just the opposite is the case. Just as Darwin and Wallace explained how the wonderful adaptations of living forms could arise without supernatural intervention, so the string landscape may explain how the constants of nature that we observe can take values suitable for life without being fine-tuned by a benevolent creator. I found this parallel well understood in a surprising place, a *New York Times* article by Christoph Schönborn, Cardinal Archbishop of Vienna [60]. His article concludes as follows.

Now, at the beginning of the 21st century, faced with scientific claims like neo-Darwinism and the multiverse hypothesis in cosmology invented to avoid the overwhelming evidence for purpose and design found in modern science, the Catholic Church will again defend human nature by proclaiming that the immanent design evident in nature is real. Scientific theories that try to explain away the appearance of design as the result of ‘chance and necessity’ are not scientific at all, but, as John Paul put it, an abdication of human intelligence.

It is nice to see work in cosmology get some of the attention given these days to evolution, but of course it is not religious preconceptions like these that can decide any issues in science.

It must be acknowledged that there is a big difference in the degree of confidence we can have in neo-Darwinism and in the multiverse. It is settled, as well as anything in science is ever settled, that the adaptations of living things on Earth have come into being through natural selection acting on random undirected inheritable variations. About the multiverse, it is appropriate to keep an open mind, and opinions among scientists differ widely. In the Austin airport on the way to this meeting I noticed for sale the October issue of a magazine called *Astronomy*, having on the cover the headline ‘Why You Live in Multiple Universes’. Inside I found a report of a discussion at a conference at Stanford, at which Martin Rees said that he was sufficiently confident about the multiverse to bet his dog’s life on it, while Andrei Linde said he would bet his own life. As for me, I have just enough confidence about the multiverse to bet the lives of both Andrei Linde *and* Martin Rees’s dog.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grants nos. PHY-0071512 and PHY-0455649 and with support from The Robert A. Welch Foundation, Grant no. F-0014, and also grant support from the US Navy, Office of Naval Research, Grant nos. N00014-03-1-0639 and N00014-04-1-0336, Quantum Optics Initiative.

References

- [1] R. Bousso and J. Polchinski. *JHEP*, **0006** (2000), 006.
- [2] L. Smolin. *Life of the Cosmos* (New York: Oxford University Press, 1997).
- [3] M. J. Duff, B. E. W. Nilsson and C. N. Pope. *Phys. Rep.* **130** (1986), 1.
- [4] S. B. Giddings, S. Kachru and J. Polchinski. *Phys. Rev. D* **66** (2002), 106006.
- [5] A. Strominger, A. Maloney and E. Silverstein. In *The Future of Theoretical Physics and Cosmology*, eds. G. W. Gibbons, E. P. S. Shellard and S. J. Ranken (Cambridge: Cambridge University Press, 2003), pp. 570–91.
- [6] S. Kachru, R. Kallosh, A. D. Linde and S. P. Trivedi. *Phys. Rev. D* **68** (2003), 046005.
- [7] S. K. Ashok and M. Douglas. *JHEP*, **0401** (2004), 060.
- [8] L. Susskind. This volume (2007) [hep-th/0302219].
- [9] S. Weinberg. *Phys. Rev. Lett.* **59** (1987), 2607.
- [10] A. Vilenkin. *Phys. Rev. Lett.* **74** (1995), 846.
- [11] J. D. Barrow and F. J. Tipler. *The Anthropic Cosmological Principle* (Oxford: Clarendon, 1986).
- [12] H. Martel, P. Shapiro and S. Weinberg. *Astrophys. J.* **492** (1998), 29.
- [13] G. Efstathiou. *Mon. Not. Roy. Astron. Soc.* **274** (1995), L73.

- [14] S. Weinberg. In *Critical Dialogues in Cosmology*, ed. N. Turok (Singapore: World Scientific, 1997).
- [15] A. G. Riess, A. V. Filippenko, P. Challis *et al.* *Astron. J.* **116** (1998), 1009.
- [16] S. Perlmutter, G. Aldering, G. Goldhaber *et al.* *Astrophys. J.* **517** (1999), 565.
- [17] D. N. Spergel, L. Verde, H. V. Peiris *et al.* *Astrophys. J. Supp.* **148**, (2003), 175.
- [18] M. R. Douglas. *Compt. Rend. Phys.* **5** (2004), 965 [hep-ph/0401004].
- [19] M. Dine, D. O’Neil and Z. Sun. *JHEP*, **0507** (2005), 014.
- [20] M. Dine and Z. Sun. *JHEP* **0601** (2006), 129 [hep-th/0506246].
- [21] V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel. *Phys. Rev. D* **57** (1998), 5480.
- [22] N. Arkani-Hamed and S. Dimopoulos. *JHEP*, **0506** (2005), 073.
- [23] G. F. Giudice and A. Romanino. *Nucl. Phys. B* **699** (2004), 65.
- [24] N. Arkani-Hamed, S. Dimopoulos, G. F. Giudice and A. Romanino. *Nucl. Phys. B* **709** (2005), 3.
- [25] A. Delgado and G. F. Giudice. *Phys. Lett. B* **627** (2005), 155 [hep-ph/0506217].
- [26] A. Arvanitaki, C. Davis, P. W. Graham, A. Pierce and J. G. Wacker. *Phys. Rev. D* **72** (2005), 075011 [hep-ph/0504210].
- [27] C. Hogan. *Rev. Mod. Phys.* **72**, 1149 (2000).
- [28] C. Hogan. This volume (2007) [astro-ph/0407086].
- [29] M. Tegmark and M. J. Rees. *Astrophys. J.* **499** (1998), 526.
- [30] J. Garriga and A. Vilenkin. *Prog. Theor. Phys. Suppl.* **163** (2006), 245 [hep-th/0508005].
- [31] N. Arkani-Hamed, S. Dimopoulos and S. Kachru [hep-th/0501082].
- [32] J. Distler and U. Varadarajan [hep-th/0507090].
- [33] T. Banks [hep-th/0011255].
- [34] A. D. Linde. *Phys. Lett.* **129 B** (1983), 177.
- [35] A. Vilenkin. *Phys. Rev. D* **27** (1983), 2848.
- [36] A. D. Linde. *Phys. Lett. B* **175** (1986), 305.
- [37] A. D. Linde. *Phys. Script.* **T 15** (1987), 100.
- [38] A. D. Linde. *Phys. Lett. B* **202** (1988), 194.
- [39] A. D. Linde. In *The Very Early Universe*, eds. G. W. Gibbons, S. W. Hawking and S. Siklos (Cambridge: Cambridge University Press, 1983).
- [40] A. D. Linde. *Rep. Prog. Phys.* **47** (1984), 925.
- [41] T. Banks. *Nucl. Phys. B* **249** (1985), 332.
- [42] L. Abbott. *Phys. Lett. B* **150** (1985), 427.
- [43] J. D. Brown and C. Teitelboim. *Phys. Lett. B* **195** (1987), 177.
- [44] J. D. Brown and C. Teitelboim. *Nucl. Phys. B* **297** (1987), 787.
- [45] J. L. Feng, J. March-Russel, S. Sethi and F. Wilczek. *Nucl. Phys. B* **602** (2001), 307.
- [46] H. Firouzjahi, S. Sarangji and S.-H. Tye. *JHEP*, **0409** (2004), 060.
- [47] B. Freivogel, M. Kleban, M. R. Martinez and L. Susskind. *JHEP* **3** (2006), 39 [hep-th/0505232].
- [48] S. W. Hawking. *Nucl. Phys. B* **239** (1984), 257.
- [49] S. W. Hawking. *Relativity, Groups, and Topology II*, NATO Advanced Study Institute Session XL, Les Houches, 1983, eds. B. S. DeWitt and R. Stora (Amsterdam: Elsevier, 1984), p. 336.

- [50] J. Hartle and S. W. Hawking. *Phys. Rev.* **D 28** (1983), 2960.
- [51] S. Coleman. *Nucl. Phys.* **B 307** (1988), 867.
- [52] S. W. Hawking. In *Shelter Island II – Proceedings of the 1983 Shelter Island Conference on Quantum Field Theory and the Fundamental Problems of Physics*, eds. R. Jackiw *et al.* (Cambridge: MIT Press, 1985).
- [53] S. W. Hawking. *Phys. Lett.* **B 134** (1984), 403.
- [54] E. Baum. *Phys. Lett.* **B 133** (1984), 185.
- [55] S. Coleman. *Nucl. Phys.* **B 310** (1985), 643.
- [56] W. Fischler, I. Klebanov, J. Polchinski and L. Susskind. *Nucl. Phys.* **B 237** (1989), 157.
- [57] H. Ooguri, C. Vafa and E. Verlinde. *Lett. Math. Phys.* **74** (2005), 311 [hep-th/0502211].
- [58] M. Livio and M. J. Rees. *Science*, **309** (2003), 1022.
- [59] M. Tegmark. *Ann. Phys.* **270** (1998), 1.
- [60] C. Schönborn. *N.Y. Times* (7 July 2005), p. A23.

3

Enlightenment, knowledge, ignorance, temptation

Frank Wilczek

Center for Theoretical Physics, Massachusetts Institute of Technology

Modified version of summary talk at the symposium *Expectations of a Final Theory* at Trinity College, Cambridge, 4 September 2005

3.1 A new zeitgeist

Our previous ‘Rees-fest’ *Anthropic Arguments in Fundamental Physics and Cosmology* at Cambridge in 2001 had much in common with this one, in terms of the problems discussed and the approach to them. Then, as now, the central concerns were apparent conspiracies among fundamental parameters of physics and cosmology that appear necessary to ensure the emergence of life. Then, as now, the main approach was to consider the possibility that significant observational selection effects are at work, even for the determination of superficially fundamental, universal parameters.

That approach is loosely referred to as anthropic reasoning, which in turn is often loosely phrased as the anthropic principle: the parameters of physics and cosmology have the values they do in order that intelligent life capable of observing those values can emerge. That formulation upsets many scientists, and rightly so, since it smacks of irrational mysticism.

On the other hand, it is simply a fact that intelligent observers are located only in a miniscule fraction of space, and in places with special properties. As a trivial consequence, probabilities conditioned on the presence of observers will differ grossly from probabilities per unit volume. Much finer distinctions are possible and useful; but I trust that this word to the wise is enough to it make clear that we should not turn away from straightforward logic just because it can be made to sound, when stated sloppily, like irrational mysticism.

For all their commonality of content, the spirit pervading the two gatherings seemed quite different, at least to me. One sign of the change is the

different name attached to the present gathering. This time it is *Expectations of a Final Theory*. The previous gathering had a defensive air. It prominently featured a number of physicists who subsisted on the fringes, voices in the wilderness who had for many years promoted strange arguments about conspiracies among fundamental constants and alternative universes. Their concerns and approaches seemed totally alien to the consensus vanguard of theoretical physics, which was busy successfully constructing a unique and mathematically perfect universe.

Now the vanguard has marched off to join the prophets in the wilderness. According to the new zeitgeist, the real world of phenomena must be consulted after all, if only to position ourselves within a perfect, but inaccessible, multiverse. Estimating selection effects, in practice, requires considerations of quite a different character than what we have become accustomed to in the recent practice of theoretical (i.e. hep-th) physics: looser and more phenomenological, less precise but more accurate.

3.2 Sources

What caused the change? In his opening talk, Steve Weinberg [1] ascribed the change in attitude to recent developments in string theory, but I think its deep roots mostly lie elsewhere and go much further back in time. Those of us who attended *Anthropic Arguments* lived through an empirical proof of that point. I would like to elaborate on this issue a little, not only as a matter of accurate intellectual history, but also to emphasize that the main arguments do not rely on narrow, delicate (I might venture to say fragile) technical developments; rather, they are broadly based and robust.

(1) *The standardization of models*

With the extraordinary success of the standard model of fundamental physics, brought to a new level of precision at LEP through the 1990s, and with the emergence of a Standard Model of cosmology, confirmed by precision measurements of microwave background anisotropies, it became clear that an excellent working description of the world as we find it is in place. This remarkable success is graphically illustrated in Figs. 3.1–3.3. In particular, the foundational laws of physics that are relevant to chemistry and biology seem pretty clearly to be in place.

The Standard Models are founded upon broad principles of symmetry and dynamics, assuming the values of a handful of numerical parameters as inputs. Given this framework, we can consider in quite an orderly way

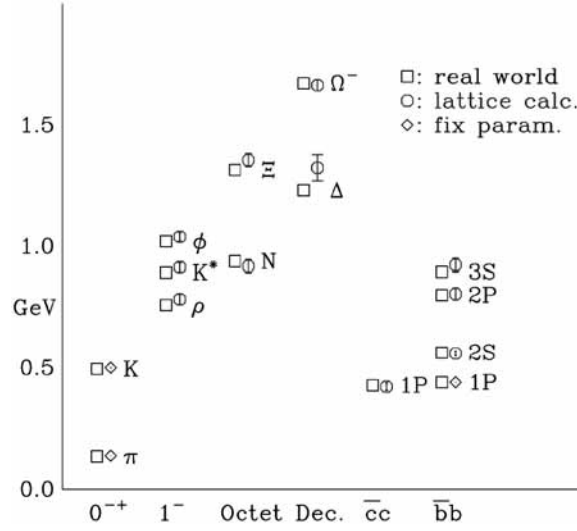


Fig. 3.1. The calculation of particle masses in QCD. N denotes the nucleon, K and K^* denote pseudoscalar and vector K mesons, and the Greek letters are standard particle designations. The spectroscopic labels $1P$, $2S$, etc. refer to heavy quark–antiquark states; their energy relative to the ground state is displayed. These calculations, which employ the full power of modern computers, account for the bulk of the mass of ordinary matter on the basis of a conceptually based yet fully algorithmic theory. Figure courtesy of D. Toussaint, compiling results from the MILC collaboration and others.

the effect of a broad class of plausible changes in the structure of the world: namely, change the numerical values of those parameters! When we try this we find, in several different cases, that the emergence of complex structures capable of supporting intelligent observation appears quite fragile.

On the other hand, valiant attempts to derive the values of the relevant parameters, using symmetry principles and dynamics, have not enjoyed much success. Thus, life appears to depend upon delicate coincidences that we have not been able to explain. The broad outlines of that situation have been apparent for many decades. When less was known, it seemed reasonable to hope that better understanding of symmetry and dynamics would clear things up. Now that hope seems much less reasonable. The happy coincidences between life's requirements and nature's choices of parameter values might be just a series of flukes, but one could be forgiven for beginning to suspect that something deeper is at work. That suspicion is the first deep root of anthropic reasoning.

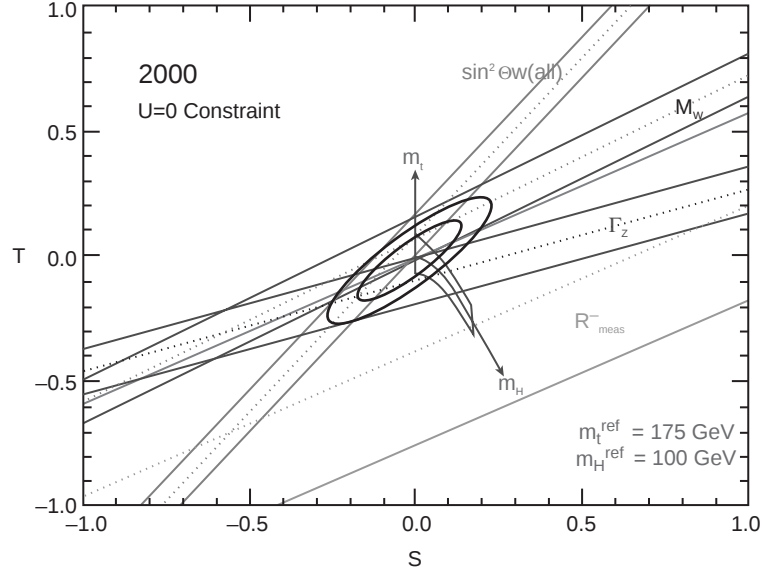


Fig. 3.2. Overdetermined, precision comparison of theory and experiment in electroweak theory, including radiative corrections. The calculations make ample use of the intricate rules for dealing with virtual particles in quantum field theory. Successful confrontations between theory with experiment, of the sort shown here and in Fig. 3.1, established our Standard Model of fundamental interactions. T and S are dimensionless parameters describing the deviations from this model. Figure courtesy of M. Swartz; for up-to-date information, consult <http://lepewwg.lep.cern.ch/LEPEWWG>.

(2) The exaltation of inflation

The most profound result of observational cosmology has been to establish the Cosmological Principle: that the same laws apply to all parts of the observed Universe, and moreover matter is – on average – uniformly distributed throughout. It seems only reasonable, then, to think that the observed laws are indeed universal, allowing no meaningful alternative, and to seek a unique explanation for each and every aspect of them. Within that framework, explanations invoking selection effects are moot. If there is no variation, then there cannot be selection.

Inflationary cosmology challenges that interpretation. It proposes a different explanation of the Cosmological Principle: that the observed universe originated from a small patch and had its inhomogeneities ironed out dynamically. In most theoretical embodiments of inflationary cosmology, the currently observed universe appears as a small part of a much larger multiverse. In this framework observed universal laws need not be multiversal, and it is valid – indeed necessary – to consider selection effects.

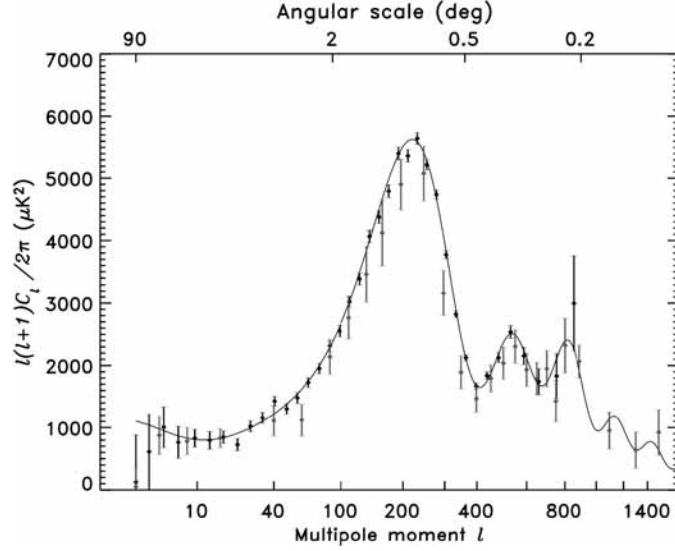


Fig. 3.3. Comparison of standard cosmological model, including dark matter, dark energy, and scale-invariant, adiabatic, Gaussian fluctuation spectrum, with observed microwave anisotropies. C_l gives the anisotropy on the angular scale $180^\circ/l$. The successful confrontation of theory and experiment in this case established our new Standard Model of cosmology. It traces the origin of all macroscopic structure to the growth of simply characterized, tiny seed fluctuations through gravitational instability. Figure courtesy of WMAP collaboration.

The success of inflationary cosmology is the second deep root of anthropic reasoning.

(3) *The unbearable lightness of spacetime*

Among the coincidences between life's requirements and nature's choices of parameter values, the smallness of the cosmological term, relative to its natural value, is especially clear and striking. Modern theories of fundamental physics posit an enormous amount of structure within what we perceive as empty space: quantum fluctuations, quark-antiquark condensates, Higgs fields, and more. At least within the framework of General Relativity, gravity responds to every sort of energy-momentum, and simple dimensional estimates of the contributions from these different sources suggest values of the vacuum energy, or cosmological term, many orders of magnitude larger than what is observed. Depending on your assumptions, the discrepancy might involve a factor of 10^{60} , 10^{120} or ∞ . Again, attempts to derive an unexpectedly small value for this parameter, the vacuum energy, have not met with success. Indeed, most of those attempts aimed to derive the value zero, which now appears to be the wrong answer.

In 1987, Weinberg proposed to cut this Gordian knot by applying anthropic reasoning to the cosmological term. On this basis, he predicted that the cosmological term, rather than being zero, would be as large as it could be, while remaining consistent with the emergence of observers. The numerical accuracy of this prediction is not overwhelmingly impressive (the computed probability to observe a cosmological term as small as we do is roughly 10%), though this might be laid to the vagaries of sampling a statistical distribution just once. Also the original calculation was based on the hypothesis that one should consider variations in the vacuum energy alone, keeping all other parameters fixed, which might be too drastic a simplification. In any case, the apparent observation of vacuum energy that is ridiculously small from a microphysical perspective, but importantly large from a cosmological perspective, certainly encourages explanation based on selection.

(4) *The superabundance of string theory*

After a brief, heady period around 1984/5, during which it seemed that simple general requirements (for example $N = 1$ supersymmetry and three light fermion generations) might pick out a unique Calabi–Yau compactification as the description of observed reality, serious phenomenological application of string theory was forestalled by the appearance of a plethora of candidate solutions. The solutions all exhibited unrealistic features (for example, unbroken supersymmetry, extraneous massless moduli fields), and it was anticipated that – when those problems were fixed – some degree of uniqueness might be restored. It was also hoped that string theory would provide a dynamical understanding for why the cosmological term is zero.

Recent constructions have provided a plethora of approximate solutions with broken supersymmetry and few or no moduli fields. They are not stable, but it is plausible that some of them are metastable, with very long lifetimes indeed. As yet none (among $\gtrsim 10^{\text{hundreds}}$) appears to be entirely realistic, but there is still plenty of scope for investigation in that direction, and even for additional constructions. In these new constructions, the cosmological term can take a wide range of values, positive or negative. So if cosmology provides a multiverse in which a significant sample of these metastable solutions are realized, then the stage might be set for selection effects to explain (roughly) the value we actually observe, as I just sketched.

3.3 Losses

Einstein expressed the traditional, maximally ambitious vision of mathematical physics with characteristic lucidity as follows [2].

I would like to state a theorem which at present can not be based upon anything more than upon a faith in the simplicity, i.e. intelligibility, of nature: there are no arbitrary constants... that is to say, nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur (not constants, therefore, whose numerical value could be changed without destroying the theory).

Over the course of the twentieth century, that programme has worked remarkably well. Rather than waste words to belabour the point, I will just present you with three icons.

What is most characteristic of these icons is their richness of detail and their quantitative precision. They confront profound theoretical ideas and complex calculations with concrete, precise observations. The fact that we physicists can worry over possible discrepancies at the level of parts per billion, in the case of the muon's magnetic moment, is our unique glory. Such examples epitomize what, traditionally, has distinguished fundamental physics from softer, 'environmental' disciplines such as history and biology.

With those words and images in mind, let me lament our prospective losses, if we adopt anthropic or statistical selection arguments too freely.

(1) *Loss of precision*

I do not see any realistic prospect that anthropic or statistical selection arguments – applied to a single sampling! – will ever lead to anything comparable in intellectual depth and numerical precision to what these icons represent. In that sense, intrusion of selection arguments into foundational physics and cosmology really does, to me, represent a genuine lowering of expectations.

(2) *Loss of targets*

Because the Standard Models of fundamental physics and cosmology describe the world so well, a major part of what ideas going beyond those Standard Models could aspire to achieve, for improving our understanding of the world, would be to fix the values of their remaining free parameters. If we compromise on that aspiration, there will be much less about the physical world for fundamental theory to target.

3.4 A classification

Of course, physicists have had to adjust their expectations before. In the development of Copernican–Newtonian celestial mechanics, attractive *a priori* ideas about the perfect shape of planetary orbits (Ptolemy) and their

origin in pure geometry (Kepler) had to be sacrificed. In the development of quantum mechanics, ideas of strict determinism (Einstein) had to be sacrificed. In those cases, sacrifice of appealing philosophical ideas was compensated for by the emergence of powerful theories that described many specific features of the natural world and made surprising, impressive predictions. In the USA we have the saying ‘No pain, no gain’.

There is a big difference, however, between those episodes and the present one. Resort to anthropic reasoning involves plenty of pain, as I have lamented, but so far the gain has been relatively meagre, to say the least. Even if we cannot be precise in our predictions of fundamental parameters, we can still aspire to clear thinking. Specifically, we can try to be clear concerning what it is we can or cannot be precise about. In this way we can limit our losses, or at least sharpen our discussion. In that spirit, I would like to suggest a chart, shown in Figs. 3.4 and 3.5, that draws some helpful boundaries.

The chart provides four boxes wherein to house parameters, or salient combinations of parameters, as in Fig. 3.4. On the horizontal axis, we have a binary distinction: is the parameter selected for, in the sense of anthropic reasoning, or not? In other words, is it relevant to the emergence of intelligent life or not? On the vertical axis, we have a different binary distinction: is the parameter one about whose values we have promising ideas based on symmetry and dynamics, or not? In that way we divide up the parameters into four classes. I have named the different classes in Fig. 3.5.

(1) *Enlightenment*

This class contains salient combinations of parameters that are both crucial to life and at least *significantly* understood. Its box is rather sparsely populated. I have entered the tiny ratio of the proton mass m_p to the Planck mass M_{Pl} . That small ratio is what allows the pull and tug of nuclear physics and chemistry, with attendant complexity, to dominate the relentless crunch of gravity. It can be understood as a consequence of the logarithmic running of the strong coupling, and the $SU(2) \times U(1)$ veto of quark and electron masses, modulo the weak-scale hierarchy problem (which opens a can of worms).

(2) *Knowledge*

This class contains parameters or regularities that do not appear to be crucial for life, but have been interpreted to have profound theoretical significance. Among these are the tiny θ parameter of QCD, the relationship among low-energy $SU(3)$, $SU(2)$ and $U(1)$ couplings that enables their unification at high energy, and the extremely long lifetime of the proton (τ_p).

		Selected?	
		Yes	No
Good Design Ideas?	Yes	$m_p \ll M_{Pl}$	$\theta_{QCD} \ll 1$ unified couplings $\tau_p \gg H^{-1}$
	No	$\rho_\lambda / (\xi^4 Q^3) \sim 10^2$ $m_e, m_u, m_d, \Lambda_{QCD} \rightarrow$ nuclear physics $m_e \ll m_W$	most M, CKM parameters most BSM parameters

Fig. 3.4. Classification of various parameters by criteria of selective pressure and theoretical insight. For definitions and discussion, see the text.

		Selected?	
		Yes	No
Good Design Ideas?	Yes	Enlightenment	Knowledge
	No	Temptation	Ignorance

Fig. 3.5. Appropriate names for the different classes of parameters. ‘Temptation’ labels the natural habitat for anthropic reasoning.

The θ parameter encodes the possibility that QCD might support violation of parity (P) and time reversal (T) in the strong interaction. It is a pure number, defined modulo 2π . Experimental constraints on this parameter require $|\theta| \lesssim 10^{-9}$, but it is difficult to imagine that life requires better than $|\theta| \lesssim 10^{-1}$, if that, since the practical consequences of nuclear P and T violation seem insignificant. On the other hand, there is a nice theoretical idea, Peccei–Quinn symmetry, that could explain the smallness of θ . Peccei–Quinn symmetry requires expansion of the Standard Model, and implies the existence of a remarkable new particle, the axion, of which more below.

The unification relationship among gauge couplings encourages us to think that the corresponding gauge symmetries are aspects of a single encompassing symmetry which is spontaneously broken, but would become manifest at asymptotically large energies or short distances. Accurate quantitative realization of this idea requires expanding the Standard Model even at low energies. Low-energy supersymmetry in any of its forms (including focus point or split supersymmetry) is very helpful in this regard. Low-energy supersymmetry, of course, requires a host of new particles, some of which should materialize at the LHC.

It is difficult to see how having the proton lifetime very much greater than the age of the Universe ($H^{-1} \sim 10^{18}$ s) could be important to life. Yet the observed lifetime is at least $\tau_p \gtrsim 10^{40}$ s. Conventional anthropic reasoning is inadequate to explain that observation. (Perhaps including potential *future* observers in the weighting will help.) On the other hand, the unification of couplings calculation implies a very high energy scale for unification, which supplies a natural suppression mechanism. Detailed model implementations, however, suggest that if gauge unification ideas are on the right track, proton decay should occur at rates not far below existing limits.

(3) *Ignorance*

This class contains parameters that are neither important to life, nor close to being understood theoretically. It includes the masses M and weak mixing angles of the heavier quarks and leptons (encoded in the Cabibbo–Kobayashi–Maskawa, or CKM, matrix) and the masses and mixing angles of neutrinos. It also includes most of the prospective parameters of models beyond the Standard Model (BSM), such as low-energy supersymmetry, because only a few specific properties of those models (for example the rate of baryogenesis) are relevant to life. Of course, if the multiverse supports enough variation to allow selection to operate among a significant fraction of the parameters that are relevant to life, there is every reason to expect variation also among some parameters that are not relevant to life. In an abundant multiverse, wherein any particular location requires specification of many independent coordinates, we might expect this box to be densely populated, as evidently it is.

(4) *Temptation*

This class contains parameters whose values are important to life, and are therefore subject to selection effects, but which look finely tuned or otherwise odd from the point of view of symmetry and dynamics. It is in understanding these parameters that we are tempted to invoke anthropic reasoning. This

class includes the smallness of the dark energy (ρ_λ), mentioned previously, and several other items indicated in Fig. 3.5.

Life in anything close to the form we know it requires both that there should be a complex spectrum of stable nuclei, and that the nuclei can be synthesized in stars. As emphasized by Hogan [3] and many others, those requirements imply constraints, some quite stringent, relating the QCD parameters $\Lambda_{\text{QCD}}, m_u, m_d$ and m_e and α . On the other hand, these parameters appear on very different footings within the Standard Model and in existing concrete ideas about extending the Standard Model. The required conspiracies *among* the masses m_u, m_d and m_e are all the more perplexing because each of the masses is far smaller than the ‘natural’ value, 250 GeV, set by the Higgs condensate. An objective measure of the degree of unnaturalness is that pure-number Yukawa couplings of order 10^{-6} underlie these masses.

More recent is the realization that the emergence of user-friendly macrostructures, that is stable planetary systems, requires rather special relationships among the parameters of the cosmological Standard Model. Here again, no conventional symmetry or dynamical mechanism has been proposed to explain those relationships; indeed, they connect parameters whose status within existing microscopic models is wildly different. Considerations of this sort have a rich literature, beginning with ref. [4]. Detailed discussion of these matters, which brings in some very interesting astrophysics, can be found in ref. [5]. (In this regard, this paper greatly improves on refs. [6] and [7] and on my summary talk as actually delivered.) A major result of the paper is a possible anthropic explanation of the observed abundance ξ of dark matter (normalized to photon number and thereby rendered time-independent), conditioned on the density of dark energy ρ_λ and the amplitude Q of primeval density fluctuations.

Dynamical versus anthropic reasoning is not an either/or proposition. It may be that some parameters are best understood dynamically and others anthropically (and others not at all). In my chart, no box is empty. Indeed, there is much potential for fertile interaction between these different modes of reasoning. For example, both axion physics and low-energy supersymmetry provide candidates for dark matter, and dark matter has extremely important anthropic implications [5]. Nor is the situation necessarily static. We can look forward to a flow of parameters along the paths from ‘ignorance’ to ‘enlightenment’ as physics progresses.

3.5 A new zeitgeist?

Actually, it is quite old. Earlier I discussed ‘losses’. There could be a compensating moral gain, however, in well-earned humility. What we are

‘losing’, we never really had. Pure thought did not supersede creative engagement with phenomena as a way of understanding the world twenty years ago, it has not in the meantime, and will not anytime soon. I think it has been poetic to witness here at Trinity a re-emergence of some of the spirit of Newton. Perhaps not yet ‘Hypothesis non fingo’, but I hope the following applies [8]:

I know not how I seem to others, but to myself I am but a small child wandering upon the vast shores of knowledge, every now and then finding a small bright pebble to content myself with while the vast ocean of undiscovered truth lay before me.

Acknowledgement

The work of FW is supported in part by funds provided by the US Department of Energy under cooperative research agreement DE-FC02-94ER40818.

References

- [1] S. Weinberg. This volume (2007) [hep-th/0511037].
- [2] A. Einstein. In *Albert Einstein, Philosopher-Scientist*, ed. P. A. Schilpp (New York: Harper Torchbooks, 1959), p. 63.
- [3] C. Hogan. *Rev. Mod. Phys.* **72** (2000), 4.
- [4] B. Carr and M. Rees. *Nature*, **278** (1979), 605.
- [5] M. Tegmark, A. Aguirre, M. Rees and F. Wilczek. *Phys. Rev. D* **73** (2006), 23505 [astro-ph/0511774].
- [6] F. Wilczek. *Phys. Rev. D* **73** (2006), 023505 [hep-ph/0408167].
- [7] F. Wilczek. This volume (2007).
- [8] I. Newton. Letter to a friend, published by Bishop Hawsley, archivist; see <http://www.newtonproject.ic.ac.uk>.

Part II

Cosmology and astrophysics

4

Cosmology and the multiverse

Martin J. Rees

Institute of Astronomy, University of Cambridge

4.1 Do the ‘special’ values of the constants of physics and cosmology need an explanation?

In his book *Galaxies, Nuclei and Quasars* [1], Fred Hoyle wrote that ‘one must at least have a modicum of curiosity about the strange dimensionless numbers that appear in physics’. Hoyle was among the first to conjecture that the so-called ‘constants of nature’ might not be truly universal. He outlined two possible attitudes to them. One is that ‘the dimensionless numbers are all entirely necessary to the logical consistency of physics’; the second possibility is that the numbers are not in the broadest sense universal, but that ‘in other places their values would be different’. Hoyle favoured this latter option because then

the curious placing of the levels in C^{12} and O^{16} need no longer have the appearance of astonishing accidents. It could simply be that, since creatures like ourselves depend on a balance between carbon and oxygen, we can exist only in the portions of the universe where these levels happen to be correctly placed.

Whatever one thinks of its motivation, Hoyle’s conjecture is now even more attractive. The ‘portions of the universe’ between which the variation occurs must now, we realise, be interpreted as themselves vastly larger than the spacetime domain our telescopes can actually observe – perhaps even entire ‘universes’ within a multiverse.

If we ever established contact with intelligent aliens, how could we bridge the ‘culture gap’? One common culture (in addition to mathematics) would be physics and astronomy. We and the aliens would all be made of atoms, and we would all trace our origins back to the big bang 13.7 billion years ago. We would all share the potentialities of a (perhaps infinite) future. But our existence (and that of the aliens, if there are any) depends on our universe being rather special. Any universe hospitable to life – what we

might call a ‘biophilic’ universe – has to be ‘adjusted’ in a particular way. The prerequisites for any life of the kind we know about – long-lived stable stars, stable atoms such as carbon, oxygen and silicon, able to combine into complex molecules etc. – are sensitive to the physical laws and to the size, expansion rate and contents of the universe in which they exist. Indeed, even for the most open-minded science fiction writer, ‘life’ or ‘intelligence’ requires the emergence of some generic complex structures: it cannot exist in a homogeneous universe or in a micro-universe containing only a few dozen particles. Many recipes would lead to stillborn universes with no atoms, no chemistry and no planets; or to universes too short-lived or too empty to allow anything to evolve beyond sterile uniformity.

Consider, for example, the role of gravity. Stars and planets depend crucially on this force; but nothing remotely like us could exist if gravity were much stronger than it actually is. In an imaginary ‘strong-gravity’ universe, stars (gravitationally bound fusion reactors) would be small; gravity would crush anything larger than an insect. But what would preclude a complex ecosystem even more would be the limited time. The mini-Sun would burn faster and would have exhausted its energy before even the first steps in organic evolution had got under way. A large, long-lived and stable universe depends quite essentially on the gravitational force being exceedingly weak. Gravity also amplifies linear density contrasts in an expanding universe; it then provides a negative specific heat so that dissipative bound systems heat up further as they radiate. There’s no thermodynamic paradox in evolving from an almost structureless fireball to the present cosmos, with huge temperature differences between the 3 K of the night sky and the blazing surfaces of stars. So gravity is crucial, but the weaker it is, the grander and more prolonged are its consequences. Newton’s constant G need not be fine-tuned – one just needs gravity to be exceedingly weak on the atomic scale compared with electrical force, so that the famous large number e^2/Gm_p^2 is indeed very large.

However, the natural world is much more sensitive to the balance between other basic forces. If nuclear forces were slightly stronger than they actually are relative to electric forces, two protons could stick together so readily that ordinary hydrogen would not exist, and stars would evolve quite differently. Some of the details – such as the carbon and oxygen abundances first noted by Hoyle – are still more sensitive, requiring some seeming ‘tuning’ in the nuclear forces.

Even a universe as large as ours could be very boring: it could contain no atoms at all – just black holes or inert dark matter. Even if it had the same ingredients as ours, it could be expanding so fast that no stars or galaxies

had time to form; or it could be so turbulent that all the material formed vast black holes rather than stars or galaxies – an inclement environment for life. And our universe is also special in having three spatial dimensions. A four-dimensional world would be unstable, there are constraints on complex networks in two dimensions, and so forth.

The distinctive and special-seeming recipe characterizing our universe seems to me a fundamental mystery that should not be brushed aside merely as a brute fact. Rather than re-addressing the classic examples of fine-tuning in the fundamental forces, I shall in this chapter focus on the parameters of the big bang – the expansion rate, the curvature, the fluctuations and the material content. Some of these parameters (perhaps even all) may be explicable in terms of a unified theory, or somehow derivable from the microphysical constants. On the other hand, they may – in some still grander perspective – be mere ‘environmental accidents’. But, irrespective of how that may turn out, it is interesting to explore the extent to which the properties of a universe – envisaged here as the aftermath of a single big bang – are sensitive to the cosmological parameters.

4.2 Is it scientific to enquire about other universes?

A semantic digression is necessary in order to pre-empt irrelevant criticism. The word ‘universe’ traditionally denotes ‘everything there is’. Therefore if we envisage that physical reality could embrace far more than traditionally believed – for instance, other domains of spacetime originating in other big bangs, or domains embedded in extra spatial dimensions – we should really define the whole ensemble as ‘the universe’, and introduce a new word – ‘meta-galaxy’ for instance – to denote what observational cosmologists traditionally study. However, so long as this whole idea remains speculative, it is probably best to continue to denote what cosmologists observe as ‘the universe’ and to introduce a new term, ‘multiverse’, for the whole hypothetical ensemble.

If our existence – or, indeed, the existence of any ‘interesting’ universe – depends on a seemingly special cosmic recipe, how should we react? There seem three lines to take: we can dismiss it as happenstance, we can invoke ‘providence’, or we can conjecture that our universe is a specially favoured domain in a still vaster multiverse.

4.2.1 *Happenstance or coincidence*

Maybe a fundamental set of equations, which some day will be written on T-shirts, fixes all key properties of our universe uniquely. It would then be

an unassailable fact that these equations permitted the immensely complex evolution that led to our emergence.

But I think there would still be something to wonder about. It is not guaranteed that simple equations permit complex consequences. To take an analogy from mathematics, consider the Mandelbrot set. This pattern is encoded by a short algorithm, but has infinitely deep structure; tiny parts of it reveal novel intricacies however much they are magnified. In contrast, you can readily write down other algorithms, superficially similar, that yield very dull patterns. Why should the fundamental equations encode something with such potential complexity, rather than the boring or sterile universe that many recipes would lead to?

One hard-headed response is that we could not exist if the laws had boring consequences. We manifestly are here, so there is nothing to be surprised about. I think we would need to know why the unique recipe for the physical world should permit consequences as interesting as those we see around us (and which, as a by-product, allowed us to exist).

4.2.2 Providence or design

Two centuries ago, William Paley introduced the famous metaphor of the watch and the watchmaker – adducing the eye, the opposable thumb and so forth as evidence of a benign Creator. These ideas fell from favour, even among most theologians, in the post-Darwinian era. However, the apparent fine-tuning in physics cannot be so readily dismissed as Paley’s biological ‘evidences’: we now view any biological contrivance as the outcome of prolonged evolutionary selection and symbiosis with its surroundings; but so far as the biosphere is concerned, the physical laws are given and nothing can react back on them.

Paley’s view of astronomy was that it was not the most fruitful science for yielding evidence of design, but ‘that being proved, it shows, above all others, the scale of [the Creator’s] operations’. Paley might have reacted differently if he had known about the providential-seeming physics that led to galaxies, stars, planets and the ninety-two natural elements of the periodic table. Our universe evolved from a simple beginning – a big bang – specified by quite a short recipe, but this recipe seems rather special. Different ‘choices’ for some basic numbers would have a drastic effect, precluding the hospitable cosmic habitat in which we emerged. A modern counterpart of Paley, the clergyman and ex-mathematical physicist John Polkinghorne, interprets our fine-tuned habitat as ‘the creation of a Creator who wills that it should be so’.

4.2.3 *A special universe drawn from an ensemble*

But there is another perspective that, as the present book testifies, is gaining more attention: the possibility that there are many ‘universes’, of which ours is just one. In the others, some laws and physical constants would be different. But our universe would not be just a random one. It would belong to the unusual subset that offered a habitat conducive to the emergence of complexity and consciousness. If our universe is selected from a multiverse, its seemingly designed or fine-tuned features would not be surprising.

Some might regard other universes – regions of space and time that we cannot observe (perhaps even in principle and not just in practice) – as being in the province of metaphysics rather than physics. Science is an experimental or observational enterprise, and it is natural to be troubled by invocations of something unobservable. But I think other universes (in this sense) already lie within the proper purview of science. It is not absurd or meaningless to ask ‘Do unobservable universes exist?’, even though no quick answer is likely to be forthcoming. The question plainly cannot be settled by direct observation, but relevant evidence can be sought, which could lead to an answer.

There is actually a blurred transition between the readily observable and the absolutely unobservable, with a very broad grey area in between. To illustrate this, one can envisage a succession of horizons, each taking us further than the last from our direct experience, as illustrated in Fig. 4.1.

Limit of present-day telescopes

There is a limit to how far out into space our present-day instruments can probe. Obviously there is nothing fundamental about this limit; it is constrained by current technology. Many more galaxies will undoubtedly be revealed in the coming decades by bigger telescopes now being planned. We would obviously not demote such galaxies from the realm of proper scientific discourse simply because they have not been seen yet.

Limit in principle at present era

Even if there were absolutely no technical limits to the power of telescopes, our observations are still bounded by a horizon, set by the distance that any signal, moving at the speed of light, could have travelled since the big bang. This horizon demarcates the spherical shell around us at which the redshift would be infinite. There is nothing special about the galaxies on this shell, any more than there is anything special about the circle that defines your horizon when you are in the middle of an ocean. On the ocean, you can see farther by climbing up your ship’s mast. But our cosmic horizon cannot be

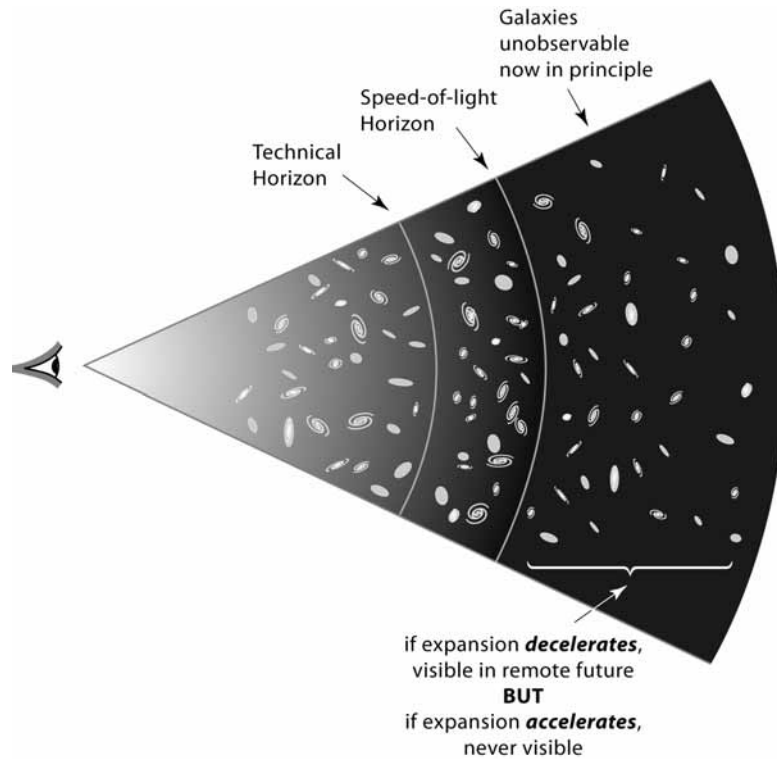


Fig. 4.1. Extending horizons beyond the directly observable, as discussed in the text.

extended unless our universe changes, so as to allow light to reach us from galaxies that are now beyond it. If our universe were decelerating, then the horizon of our remote descendants would encompass extra galaxies that are beyond our horizon today. It is, to be sure, a practical impediment if we have to await a cosmic change taking billions of years, rather than just a few decades (maybe) of technical advance before a prediction about a particular distant galaxy can be put to the test. But does that introduce a difference of principle? Surely the longer waiting time is merely a quantitative difference, not one that changes the epistemological status of these faraway galaxies?

Never-observable galaxies from 'our' big bang

But what about galaxies that we can never see, however long we wait? It is now believed that we inhabit an accelerating universe. As in a decelerating universe, there would be galaxies so far away that no signals from them have yet reached us; but if the cosmic expansion is accelerating, we are

now receding from these remote galaxies at an ever-increasing rate, so if their light has not yet reached us, it never will. Such galaxies are not merely unobservable now – they will be beyond our horizon forever. But if a galaxy is now unobservable, it hardly seems to matter whether it remains unobservable for ever, or whether it would come into view if we waited a trillion years. (And as I have argued above, the latter category should certainly count as ‘real’.)

Galaxies in disjoint universes

The never-observable galaxies discussed above would have emerged from the same big bang as we did. But suppose that, instead of causally disjoint regions emerging from a single big bang (via an episode of inflation), we imagine separate big bangs. Are spacetimes completely disjoint from ours any less real than regions that never come within our horizon in what we would traditionally call our own universe? Surely not – so these other universes should count as real parts of our cosmos too.

Whether other universes exist or not is a scientific question. Those who are prejudiced against the concept should regard the above step-by-step argument as an exercise in ‘aversion therapy’. In this technique, someone terrified of spiders is first reconciled to a small one a long way away and then, stage by stage, to a tarantula crawling all over him. Likewise, from a reluctance to deny that galaxies with redshift 10 are proper objects of scientific enquiry, you are led towards taking seriously quite separate spacetimes, perhaps governed by quite different ‘laws’.

Some theorists envisage an ‘eternal’ inflationary phase, where many universes sprout from separate big bangs into disjoint regions of spacetimes – each such region itself vastly larger than our observational horizon. Others have, from different viewpoints, suggested that a new universe could sprout inside a black hole, expanding into a new domain of space and time inaccessible to us. As a further alternative, other universes could exist, separated from us in an extra spatial dimension; these disjoint universes may interact gravitationally or they may have no effect whatsoever on each other. (Bugs crawling on a large sheet of paper – their two-dimensional universe – would be unaware of other bugs on a separate sheet of paper. Likewise, we would be unaware of our counterparts on another ‘brane’ separated in an extra dimension, even if that separation were only by a microscopic distance.) Other universes could be separate domains of space and time. We could not even meaningfully say whether they existed before, after or alongside our own, because such concepts make sense only insofar as we can impose a single measure of time, ticking away in all the universes.

None of these scenarios has been simply dreamed up out of the air; each has a serious, albeit speculative, theoretical motivation. However, one of them, at most, can be correct. Quite possibly none is; there are alternative theories that would lead just to one finite universe. Firming up any of these ideas will require a theory that consistently describes the extreme physics of ultra-high densities, how structures on extra dimensions are configured, etc. But consistency is not enough; there must be grounds for confidence that such a theory is not a mere mathematical construct, but applies to external reality. We would develop such confidence only if the theory accounted for things we can observe that are otherwise unexplained.

At the moment, the formulae of the ‘Standard Model’ involve numbers which cannot be derived from the theory but have to be inserted from experiment. Perhaps, in the twenty-first century, physicists will develop a theory that yields insight into (for instance) why there are three kinds of neutrinos and the nature of the nuclear and electric forces. Such a theory would thereby acquire credibility. If the same theory, applied to the very beginning of our universe, were to predict many big bangs, then we would have as much reason to believe in separate universes as we now have for believing inferences from particle physics about quarks inside atoms, or from relativity theory about the unobservable interior of black holes.

4.3 Universal laws or mere by-laws?

Are the laws of physics unique? This is a less poetic version of the famous question that Einstein once posed to his assistant, Ernst Strauss: ‘Did God have any choice when he created the universe?’ Offering an answer is a key scientific challenge for the new century. The answer determines how much variety the other universes – if they exist – might display. If there were something uniquely self-consistent about the actual recipe for our universe, then the aftermath of any big bang would be a re-run of our own universe. But a far more interesting possibility (which is certainly tenable in our present state of ignorance of the underlying laws) is that the underlying laws governing the entire multiverse may allow variety among the universes. Some of what we call ‘laws of nature’ may in this grander perspective be local by-laws, consistent with some overarching theory governing the ensemble, but not uniquely fixed by that theory. Many things in our cosmic environment – for instance, the exact layout of the planets and asteroids in our Solar System – are accidents of history. Likewise, the recipe for an entire universe may be arbitrary.

More specifically, some aspects may be arbitrary and others not. There could be a complementarity between chance and necessity, just as arises in biology, where our basic development – from embryo to adult – is encoded in our genes, but many aspects of our development are moulded by our environment and experiences. And there are far simpler examples of the same dichotomy. As an analogy (which I owe to Paul Davies), consider the form of snowflakes. Their ubiquitous six-fold symmetry is a direct consequence of the properties and shape of water molecules. But snowflakes display an immense variety of patterns because each is moulded by its micro-environments; how each flake grows is sensitive to the fortuitous temperature and humidity changes during its growth.

If physicists achieved a fundamental theory, it would tell us which aspects of nature were direct consequences of the bedrock theory (just as the symmetrical template of snowflakes is due to the basic structure of a water molecule) and which are (like the distinctive pattern of a particular snowflake) the outcome of accidents. Some of the accidental features could be imprinted during the cooling that follows the big bang, rather as a piece of red-hot iron becomes magnetised when it cools down, but with an alignment that may depend on chance factors. They could have other contingent causes, such as the influence of another nearby universe separated from ours in a fourth spatial dimension. Or they could simply depend on which particular oasis in the ‘cosmic landscape’ (to use Susskind’s phrase) we happen to inhabit.

At the moment, as is evident from other chapters in this book, there is no consensus on the answer to Einstein’s question: there could be a unique physics; there could, alternatively, be googles of alternative laws. Some theorists have strong preferences and prejudices favouring the former; they want as many features as possible of our universe to be ‘explained’ by neat formulae – indeed they yearn to discover these formulae themselves. But there is no reason why our universe has to accord with our aesthetic taste; the rational stance now is surely to be open-minded on this basic issue. The outcome determines which side of the ‘fork’ is taken in the decision tree of Fig. 4.2: in the one case, anthropic reasoning is irrelevant; in the other, it is unavoidable.

The cosmological numbers in our universe, and perhaps some of the so-called constants of laboratory physics as well, could be environmental accidents, rather than uniquely fixed throughout the multiverse by some final theory. Some seemingly fine-tuned features of our universe could then only be explained by anthropic arguments, as indicated by the right fork of Fig. 4.2. Although this style of explanation raises hackles among some

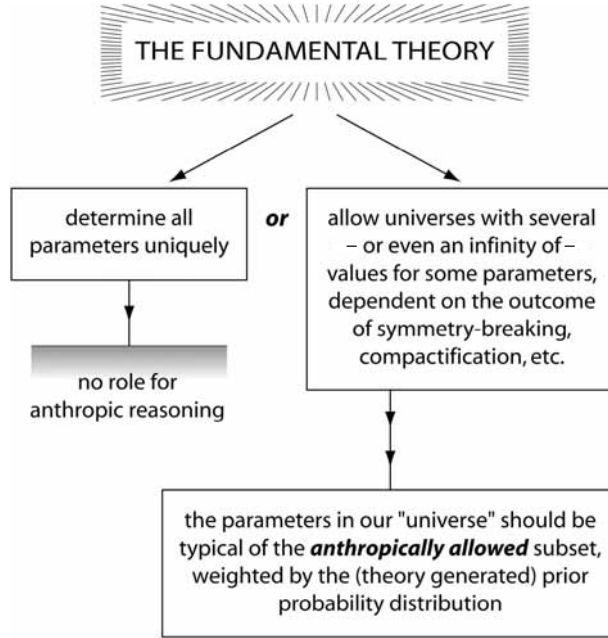


Fig. 4.2. Decision tree. Progress in twenty-first-century physics should allow us to decide whether anthropic explanations are irrelevant or the best we can ever hope for.

physicists, it is analogous to what any observer or experimenter does when they allow for selection effects in their measurements; if there are many universes, most of which are not habitable, we should not be surprised to find ourselves in one of the habitable ones!

The entire history of our universe could be just an episode of the infinite multiverse; what we call the laws of nature (or some of them) may be just parochial by-laws in our cosmic patch. Such speculations dramatically enlarge our concept of reality. Putting them on a firm footing must await a successful fundamental theory that tells us whether there could have been many big bangs rather than just one, and (if so) how much variety they might display. We will not know whether anthropic arguments are irrelevant or unavoidable until this fundamental issue is settled one way or the other.

4.4 Testing multiverse theories here and now: the value of Λ

While we are waiting for that theory – and it could be a long wait – we can check whether anthropic selection offers a tenable explanation for the

apparent fine-tuning. Some hypotheses can even be refuted; this would happen if our universe turned out to be even more specially tuned than our presence requires. Let me give two quite separate examples of this style of reasoning.

(i) Boltzmann argued that our entire universe was an immensely rare ‘fluctuation’ within an infinite and eternal time-symmetric domain. Even when it was proposed, one could already have argued powerfully against it by noting that fluctuations in large volumes are far more improbable than in smaller volumes. If Boltzmann were right, we would be in the smallest fluctuation compatible with our awareness – indeed, the overwhelmingly most likely configuration would be a universe containing nothing but a single brain with external sensations fed into it. Whatever our assessment of the prior probability of Boltzmann’s theory, its probability would plummet as we came to believe non-solipsistically in the extravagant scale of the cosmos.

(ii) Even if we knew nothing about how stars and planets formed, we would not be surprised to find that the Earth’s orbit was moderately close to circular; had it been highly eccentric, water would boil when the Earth was at perihelion and freeze at aphelion – a harsh environment unconducive to our emergence. However, a modest orbital eccentricity, up to 0.1 or so, is plainly not incompatible with life. Had it turned out that the Earth moved in a near-perfect circle with eccentricity 0.000 001, then this would need some explanation: anthropic selection from orbits whose eccentricities had a Bayesian prior that was uniform in the range 0–1 could plausibly account for an eccentricity of 0.1, but not for one as tiny as this.

In Section 4.5, I will mention several applications of this line of reasoning. But first let us recall the one that has already been extensively discussed in the literature: the cosmological constant Λ . Interest in Λ has, of course, been hugely boosted recently through the convergence of several lines of evidence on a model where the universe is flat, but with about 4% in baryons, 25% in dark matter and the remaining (dominant) component in dark energy or quintessence.¹

Most physicists would consider the ‘natural’ value of Λ to be large, because it is a consequence of a very complicated Planck-scale microstructure of

¹ The resurrection of Λ would be a great ‘coup’ from de Sitter. His model, dating from the 1920s, not only describes inflation, but would then also describe future aeons of our cosmos with increasing accuracy. Only for the fifty or so decades of logarithmic time between the end of inflation and the present would it need modification!

space. There might then be only a rare subset of universes where Λ was below the threshold that allows galaxies and stars to form before the cosmic repulsion takes over. In our universe, Λ obviously had to be below that threshold.

On the specific hypothesis that our universe is drawn from an ensemble in which Λ was equally likely to take any value, we would not expect it to be too far below the anthropic upper limit. Current evidence suggests that, if Λ constitutes the dark energy, its actual value is five to ten times below that threshold. That would put our universe between the 10th or 20th percentile of universes in which galaxies could form. In other words, our universe would not be significantly more special, with respect to Λ , than our emergence demanded. But suppose that (contrary to current indications) observations showed that Λ made no discernible contribution to the expansion rate, and was thousands of times below the threshold. This ‘overkill precision’ would raise doubts about the hypothesis that Λ was equally likely to have any value. It would suggest instead that it was zero for some fundamental reason or that the physics favoured values very close to zero or that Λ had a discrete set of possible values and all the others were well above the ‘anthropic limit’.

In this example, one is essentially asking if our actual universe is ‘typical’ of the subset in which we could have emerged. The methodology requires us to decide what domain (in some multi-parameter space) is compatible with our emergence. But it requires something else as well: a specific theory that gives the relative Bayesian priors for any particular point within that domain (for example in the case of Λ , whether there is a uniform probability density, whether low values are favoured, whether there is a set of discrete values). When applied to the important numbers of physics and cosmology, this style of reasoning can test whether our universe is (under specific theoretical assumptions about the ensemble) typical of the subset that could harbour complex life. If our universe turns out to be a grossly atypical member, even of the anthropically allowed subset (not merely of the entire multiverse), then we would not necessarily need to abandon the hypothesis of anthropic selection, but we would certainly be forced to modify our model of the underlying physics and to seek an alternative theory that had a different distribution of priors. This involves subtle and still controversial issues that I will skate over here. In particular, what relative ‘weight’ does one give different volumes and how are infinities handled? (See ref. [2] for a brave attempt to confront these issues in the context of inflationary cosmology.)

4.5 Anthropic constraints on other cosmological numbers

Traditionally, cosmology was the quest for a few numbers. The first were the Hubble parameter H and the deceleration parameter q . Since the discovery of the microwave background in 1965, we have had another: the baryon/photon ratio of about 10^{-9} . This is believed to result from a small favouritism for matter over antimatter in the early universe – something that was addressed in the context of ‘grand unified theories’ in the 1970s. (Indeed, baryon non-conservation seems a prerequisite for any plausible inflationary model. Our entire observable universe, containing at least 10^{79} baryons, could not have inflated from something microscopic if the baryon number were strictly conserved.)

In the 1980s, non-baryonic dark matter became almost a natural expectation and $\rho_{\text{dm}}/\rho_{\text{bar}}$ is another fundamental number. We now seemingly have the revival of the cosmological constant (or some kind of dark energy, with negative pressure, which is generically equivalent to this). Another specially important dimensionless number tells us how smooth our universe is. It is measured by: (a) the amplitude of the gravitationally induced fluctuations in the microwave background; (b) the gravitational binding energy of clusters as a fraction of their rest mass; or (c) the square of the typical scale of mass-clustering as a fraction of the Hubble scale. It is, of course, somewhat oversimplified to represent this by a single number,² but insofar as one can, its value (let us call it Q) is pinned down to be around 10^{-5} .

We can make a list of what would be required for a big bang to yield an anthropically allowed universe – a universe where some kind of generic complexity could unfold, whether it were humanoid or more like Fred Hoyle’s fictional ‘Black Cloud’. The list would include the following.

Some inhomogeneities (i.e. a non-zero Q): clearly there is no potential for complexity if everything remains dispersed in a uniform ultra-dilute medium.

Some baryons: complexity would be precluded in a universe solely made of dark matter, with only gravitational interactions.

At least one star: nucleosynthesis is a precondition for complex chemistry, though perhaps superfluous for Black-Cloud-style complexity.

² Detailed modelling of the fluctuations introduces further numbers: the ratio of scalar and tensor amplitudes and quantities such as the ‘tilt’, which measure the deviation from a pure scale-independent Harrison–Zeldovich spectrum.

Some second-generation stars: only later-generation stars would be able to have orbiting planets, unless heavy elements were primordial.

It is interesting to engage in ‘counterfactual history’ and ask what constraints these various requirements would impose not only on Λ (as discussed in the previous section) but on other key cosmological parameters, such as the fluctuation amplitude Q (about 10^{-5} in our universe); the baryon/photon ratio (about 10^{-9} in our universe); the baryon/dark matter density ratio (about 0.2 in our universe).

4.5.1 The fluctuation amplitude

What structures might emerge in a universe that was initially smoother (Q smaller) or rougher (Q larger) than ours? Were Q of order 10^{-6} , there would be no clusters of galaxies; moreover, the only galaxies would be small and anaemic. They would form much later than galaxies did in our actual universe. Because they would be loosely bound, processed material would be expelled from shallow potential wells; there may therefore be no second-generation stars and no planetary systems. If Q were even smaller than 10^{-6} , there would be no star formation at all; very small structures of dark matter would turn around late and their constituent gas would be too dilute to undergo the radiative cooling that is a prerequisite for star formation.³

Hypothetical astronomers in a universe with $Q = 10^{-4}$ might find their cosmic environment more varied and interesting than ours. Galaxies and clusters would span a wider range of masses. The biggest clusters would be 1000 times more massive than any in our actual universe. There could be individual galaxies – perhaps even disc galaxies – with masses up to that of the Coma cluster and internal velocity dispersions up to 2000 km s^{-1} . These would have condensed when the age of our universe was only $3 \times 10^8 \text{ y}$ and when Compton cooling on the microwave background was still effective.

However, a universe where Q were larger still – more than (say) 10^{-3} – would be a violent and inhospitable place. Huge gravitationally bound systems would collapse, trapping their radiation and being unable to fragment, soon after the epoch of recombination. (Collapse at, say, 10^7 y would lead to sufficient partial ionization via strong shocks to recouple the baryons and the primordial radiation.) Such structures, containing the bulk of the material,

³ In a Λ -dominated universe, isolated clumps could survive for an infinite time without merging into a larger scale in the hierarchy. So eventually, for any $Q > 10^{-8}$, a ‘star’ could form – but by that time it might be the only bound object within the horizon.

would turn into vast black holes. It is unlikely that galaxies of any kind would exist; nor is it obvious that much baryonic material would ever go into stars. Even if it did so, they would be in very compact highly bound systems.⁴

According to most theories of the ultra-early universe, Q is imprinted by quantum effects: microscopic fluctuations, after exponential expansion, give rise to the large-scale irregularities observed in the microwave background sky, which are the seeds for galaxies and clusters. In a wide class of theories, Q depends on the detailed physics during an inflationary era. But, as yet, no independent evidence constrains such theories, so we cannot pin down Q .

4.5.2 *The baryon/photon and baryon/dark matter density ratios*

Baryons are anthropically essential. They need not be the dominant constituent (indeed they are far from dominant in our actual universe), but there must be enough of them to allow a gas cloud of at least a few solar masses to accumulate in some of the gravitationally bound halos of dark matter. However, a more restrictive lower limit may come from the requirement that this gas should be dense enough to cool. (The cooling timescale of a gas at a given temperature depends inversely on its density.) Lower ratios of baryons to dark matter would reduce the ‘efficient cooling’ domain shown in Fig. 4.3 [3].

If the photons outnumbered the baryons and the dark matter particles by a still larger factor than in our actual universe, then the universe would remain radiation-dominated for so long that the gravitational growth of fluctuations would be inhibited [4].⁵ Suppose, on the other hand, that the baryon/photon ratio has its actual value, but the dark matter density is higher. Wilczek [5] has offered an interesting motivation for exploring this option; he suggests that, if axions constitute the dark matter, their density is lower than one would expect in a ‘typical’ universe. A higher value of $\rho_{\text{dm}}/\rho_{\text{bar}}$ reduces the

⁴ Note that, irrespective of these anthropic constraints on its value, Q has to be substantially less than unity in order to make cosmology a tractable subject, separate from astrophysics. This is because the ratio of the length scales of the largest structures to the Hubble radius is of order $Q^{1/2}$. As an analogy, contrast a view from mid-ocean with a mountain landscape. On the ocean, we can define averages because even the biggest wave is small compared with the horizon distance; but we cannot do this in the mountain landscape. Quantities like ρ , ρ_{dm} and H are only well defined insofar as our universe possesses ‘broad brush’ homogeneity – so that our observational horizon encompasses many independent patches, each big enough to be a fair sample. This would not be so, and the simple Friedmann models would not be useful approximations, if Q were not much less than unity.

⁵ Note also that the mechanism that gives rise to baryon favouritism may be linked to the strong interactions, and therefore correlate with key numbers in nuclear physics.

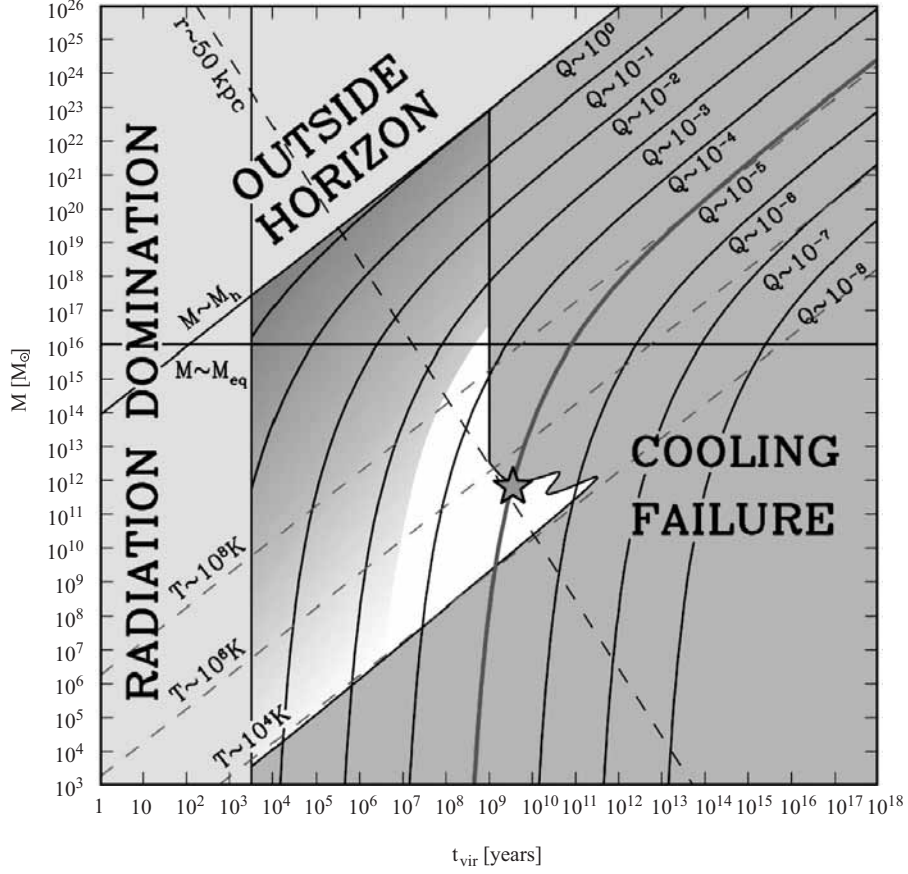


Fig. 4.3. The mass and time domains in which bound structures can form for different values of Q [3].

baryon fraction in dark halos. On the other hand, the enhanced density of dark matter compared to radiation reduces the time t_{eq} before which radiation mass-energy is dominant, thereby allowing gravitational clustering to start earlier. This reduces the minimum Q required for emergence of non-linear structures (see ref. [6]). Even if Q were 10^{-8} , dwarf galaxies could form in a universe where the dark matter density was 100 times higher (relative to the baryon density) than it is in our universe.

4.5.3 Delineating the anthropically allowed domain

In the above, I have envisaged changing just one parameter at a time, leaving the others with their actual values. But, of course, there may be correlations

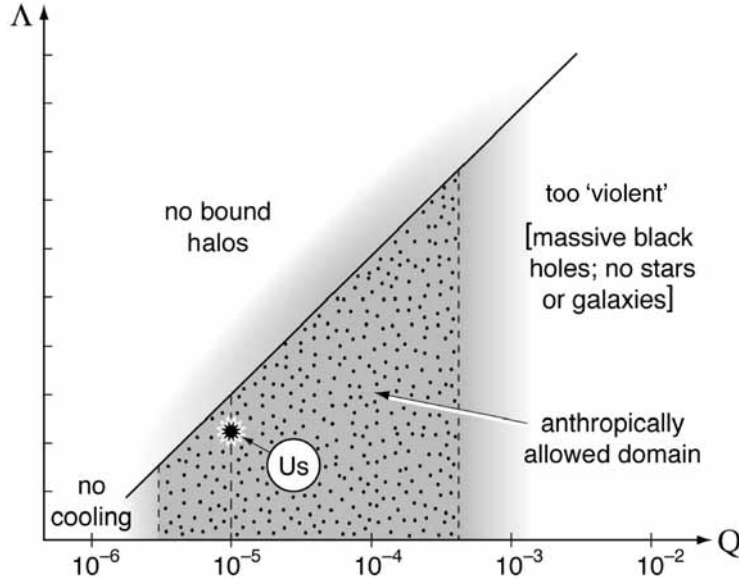


Fig. 4.4. This shows the two-dimensional parameter space associated with Λ and Q . The upper and lower limits to Q are discussed in ref. [3]. The upper limit to Λ stems from the requirement that galactic-mass bound systems should form. Our universe (obviously) lies in the anthropically allowed domain. But we cannot say whether it is at a typical location without a specific model for the probability distributions of Q and Λ in the ensemble.

between them. As a two-dimensional example, consider the joint constraints on Λ and Q , as illustrated in Fig. 4.4. There is an anthropically allowed area in the Λ – Q plane. There are (rather vaguely defined) upper and lower limits to Q (as discussed in Section 4.5.1), but within that range we do not know the probability distribution of different values.

Suppose that there were big bangs with a whole range of Q -values. Structures form earlier (when the matter density is higher) in universes with larger Q , so obviously a higher Q is anthropically compatible with a higher Λ (indeed the limit to Λ scales as Q^3). We cannot decide whether our observable universe is typical without a theory that tells us what ‘measure’ to put on each part of the two-dimensional parameter space. If high- Q universes were more probable, and the probability density of Λ were uniform, then we should be surprised not to find ourselves in a universe with higher Λ and higher Q . We would be led to seek an alternative theory that led to a distribution of priors that made our universe less surprising and one in which the probabilities were steeply weighted in favour of low Q .

We can carry out the exercise in as many dimensions as we wish – including, for instance, the ratios of the photon, baryon and dark matter densities, as discussed above. Other parameters could be analyzed similarly – testing in a multi-parameter space whether our universe is a typical member within the anthropically allowed domain.

4.6 Conclusions

The examples in Section 4.5 show that some claims about other universes may, in principle, be refutable, as any good hypothesis in science should be. To delineate the anthropically allowed domains is procedurally uncontroversial, but what about the motivation? It obviously depends on believing that the laws of nature could have been otherwise and that there is some scientific validity in imagining ‘counterfactual universes’. It obviously is predicated on the hope that theoretical ideas may sometime become sufficiently well developed to allow us to put some probability measure on the ensemble.

We cannot confidently assert that there were many big bangs – we just do not know enough about the ultra-early phases of our own universe. Nor do we know whether the underlying laws are ‘permissive’. Settling this issue is a challenge to twenty-first-century physicists. But if they are, then so-called anthropic explanations would become legitimate – indeed they would be the only type of explanation we will ever have for some important features of our universe.

Moreover, the outcome of this issue (which path in the decision tree in Fig. 4.2 is the correct one) affects our attitude to our actual observable universe. Models with low Ω , non-zero Λ , two kinds of dark matter etc. may seem ugly. Some theorists are upset by these developments, because it frustrates their craving for maximal simplicity. There is perhaps an analogy with cosmological debates in the seventeenth century. Galileo and Kepler were upset that planets moved in elliptical orbits, not in perfect circles. Newton later showed, however, that all elliptical orbits could be understood by a single unified theory of gravity – something which would surely have elated Galileo. We have learnt that our Solar System is just one of a vast number (many millions even within our Galaxy). Likewise, what we have traditionally called our universe may be an infinitesimal part of physical reality – no more than one twig on one tree in a geometrical structure as complex as a biosphere. Our capacity to explain the cosmic parameters may then be limited, but to regard this outcome as ugly may be as myopic as Kepler’s infatuation with circles.

References

- [1] F. Hoyle. *Galaxies, Nuclei and Quasars* (New York: Harper and Row, 1965).
- [2] M. Tegmark, A. Aguirre, M. J. Rees and F. Wilczek. *Phys. Rev. D* **73** (2006), 23505.
- [3] M. Tegmark and M. J. Rees. *Astrophys. J.* **499** (1998), 526.
- [4] M. J. Rees. *Phys. Script.* **21** (1980), 614.
- [5] F. Wilczek. This volume (2007).
- [6] A. Aguirre. *Phys. Rev. D* **64** (2001), 3508.

5

The Anthropic Principle revisited

Bernard Carr

Astronomy Unit, Queen Mary, University of London

5.1 Introduction

My brief historical overview in Chapter 1 alluded to the crucial influence of the Newtonian mechanistic picture on the development of our view of the Universe. According to this, the cosmos operates like a giant machine, oblivious to whether life or any form of consciousness is present, i.e. the laws of physics and the characteristics of the Universe are independent of whether anybody actually observes them. In the last fifty years, however, the Anthropic Principle has developed [1], and this might be regarded as a reaction to the mechanistic view. This claims that, in some respects, the Universe has to be the way that it is because otherwise it could not produce life and we would not be here speculating about it. Although the term ‘anthropic’ derives from the Greek word for ‘man’, it should be stressed that most of the arguments pertain to life in general.

As a simple example of an anthropic argument, consider the following question: why is the Universe as big as it is? The mechanistic answer is that, at any particular time, the size of the observable Universe is the distance travelled by light since the Big Bang, which is about 10^{10} light-years. There is no compelling reason the Universe has the size it does; it just happens to be 10^{10} y old. There is, however, another answer to this question, which Robert Dicke [2] first gave in 1961. In order for life to exist, there must be carbon, and this is produced by cooking inside stars. The process takes about 10^{10} y, so only after this time can stars explode as supernovae, scattering the newly baked elements throughout space, where they may eventually become part of life-evolving planets. On the other hand, the Universe cannot be *much* older than 10^{10} y, else all the material would have been processed into stellar remnants. Since all the forms of life we can envisage require stars, this suggests that it can only exist when the

Universe is aged about 10^{10} y. So the very hugeness of the Universe, which seems at first to point to our insignificance, is actually a prerequisite of our existence. This is not to say that the Universe itself could not exist with a different size, only that we could not be aware of it then.

Dicke's argument is an example of what is called the 'Weak Anthropic Principle' and is no more than a logical necessity [3]. This accepts the constants of nature as given and then shows that our existence imposes a selection effect on when (and where) we observe the Universe. Finding that we live at a particular *time* is no more surprising than finding that we live at a particular *place* (e.g. on a planet near a star). Much more controversial is the 'Strong Anthropic Principle', which – in the sense that I will use the term – says that there are relationships between the coupling constants (i.e. the dimensionless numbers which characterize the strengths of the four forces) and other physical quantities which are necessary in order for observers to arise. Some of these relationships are remarkably 'fine-tuned' and do not seem to be predicted by standard physics.

Chapter 1 also referred to the paper on the subject I wrote for *nature* in 1979 with Martin Rees [4]. This turned out to be quite an influential article because it brought together all the anthropic arguments that were known at the time. In this chapter I will revisit some of these arguments to see how their status has changed. However, I will not give the full details since they can be found in our original paper and also in ref. [1]. I will then consider how one might interpret the anthropic relationships and discuss whether the multiverse proposal provides the best conceptual basis for understanding them. Naturally, other contributors will consider this point – since it is one of the main themes of the book – but without coming to any general consensus.

5.2 Status of the anthropic coincidences

My focus here will be entirely on the strong anthropic arguments, since I have always regarded the weak ones as relatively uncontroversial. The first set of fine-tunings involved the four dimensionless coupling constants. These were taken to be $\alpha \sim 10^{-2}$ for electromagnetism, $\alpha_G \sim 10^{-40}$ for gravity, $\alpha_W \sim 10^{-10}$ for the weak force and $\alpha_S \sim 10$ for the strong force. The second set of fine-tunings was associated with the formation of galaxies and their subsequent fragmentation into stars. These involved various cosmological parameters, such as the matter density in units of the critical density Ω , the amplitude of the density fluctuations Q on entering the cosmological particle horizon and the photon-to-baryon ratio S . At the time, it

was not clear which of these parameters were determined by processes in the early Universe rather than being prescribed freely as part of the initial conditions.

- One of the most striking anthropic tunings was associated with the existence of stars with convective and radiative envelopes. Both types of star can exist only if α_G is roughly the 20th power of α [5]. This is because the critical mass which divides these types of stars is roughly $\alpha_G^{-2}\alpha^{10}m_p$, whereas the expected masses of stars span a few decades around $\alpha_G^{-3/2}m_p$ (m_p being the proton mass). The relationship $\alpha_G \sim \alpha^{20}$ is clearly satisfied numerically, but physics does not explain *why* this relationship should pertain. Its anthropic significance is that only radiative stars can end their lives as supernovae, which is required to disseminate heavy elements, whereas only convective stars may generate winds in their early phase, and this may be associated with the formation of rocky planets. To my mind, this is still the most striking coincidence because of the high power of α involved. Recently, Page has discussed the argument in more detail [6] and has shown that it constrains the electron charge ($e \propto \sqrt{\alpha}$) to 3%.
- We also found that α_G must be roughly the 4th power of α_W in order for neutrinos to eject the envelope of a star in a supernova explosion. If the weak force were weaker, the neutrinos would stream through the stellar surface unimpeded; if it were much stronger, they would be trapped inside the core and never reach the surface. At the time, it was not certain that neutrinos were responsible for supernovae, but this is now the standard view, although the full details are still not understood. We pointed out that the same coincidence explains why an interesting amount of helium (roughly 23% by mass) is produced by cosmological nucleosynthesis. This scenario is now undisputed and provides one of the main pillars of support for the Big Bang theory. However, the amount of helium produced is very sensitive to the temperature at which the weak interactions ‘freeze out’. If $\alpha_G < \alpha_W^4$, this would occur later and the amount of helium would be drastically reduced. If $\alpha_G > \alpha_W^4$, it would occur earlier and almost all the nucleons would burn into helium, preventing the formation of hydrogen-burning stars. At least the latter condition might be anthropically excluded, since helium-burning stars may be too short-lived for life to evolve on surrounding planets.
- Perhaps the most famous anthropic tuning concerned the generation of carbon (a prerequisite for our form of life) in the helium-burning phase of red giant stars via the triple-alpha reaction: two alpha particles first combine to form beryllium and this then combines with a third alpha particle

to form carbon. However, as Hoyle first pointed out [7], the beryllium would decay before interacting with another alpha particle were it not for the existence of a remarkably finely tuned resonance in this interaction. This is sometimes regarded as an anthropic ‘prediction’ because Hoyle’s paper prompted nuclear physicists to look for the resonance and they did indeed find it. At the time, we were unable to quantify this coincidence, but recent work by Oberhummer and colleagues – calculating the variations in oxygen and carbon production in red giant stars as one varies the strength and range of the nucleon interactions – indicates that the nuclear interaction strength must be tuned to at least 0.5% if one is to account for this [8].

- We discussed several constraints involving α_S which are associated with chemistry, although these were subsequently examined in more detail by Barrow and Tipler [1]. For example, if α_S were increased by 2%, all the protons in the Universe would combine at Big Bang nucleosynthesis into diprotons. In this case, there could be no hydrogen-burning stars, so – as mentioned above – there might not be time for life to arise. If α_S were increased by 10%, the situation would be even worse because everything would go into nuclei of unlimited size and there would be no interesting chemistry. This would also apply if α_S were decreased by 5% because all deuterons would then be unbound and one could only have hydrogen. In addition, there are chemistry-related fine-tunings involving the electron and proton masses ($m_e/m_p \sim 10\alpha^2$) and the neutron–proton mass difference ($m_n - m_p \sim 2m_e$). Of course, from the modern perspective, α_S , m_p and m_e are no longer such fundamental quantities; the QCD interaction strength and quark masses would be regarded as more important [9]. Nevertheless, fine-tuning is still required at some level.
- We stressed the (already well known) anthropic reasons for why the total density parameter Ω must lie within an order of magnitude of unity. If it were much larger than unity, the Universe would recollapse on a timescale much less than the main-sequence time of a star. On the other hand, if it were much smaller than unity, density fluctuations would stop growing before galaxies could bind. This argument required that Ω be in the range 0.1 to 10. However, one year later early Universe studies were revolutionized by the introduction of the inflation scenario [10]. This *required* that Ω be very close to unity (so that the geometry of the Universe must be very nearly ‘flat’), and observations of the microwave background radiation have subsequently confirmed this [11]. Therefore anthropic considerations may no longer seem relevant. On the other hand, it must be stressed that the inflationary explanation for flatness only works if the form of the

vacuum potential $V(\phi)$ allows a sufficient number of expansion e -folds, and this form may itself be constrained anthropically [12]. Similar considerations apply in quantum cosmology, where the Universe is expected to collapse very quickly unless one imposes anthropic selection effects [13].

- We also obtained various anthropic constraints on the photon-to-baryon ratio $S \sim 10^9$. In the standard Big Bang model, the formation of galaxies cannot occur until the background radiation density falls below the matter density, but this occurs after the time invoked in the Dicke argument (i.e. the main-sequence lifetime of a star) for $S > \alpha_G^{-1/4} \sim 10^{10}$. On the other hand, if one requires that the Universe be radiation-dominated at cosmological nucleosynthesis, to avoid all the hydrogen going into helium, one requires $S > (m_p/m_e)^{4/3}(\alpha_W^4/\alpha_G)^{1/6} \sim 10^4$. Nowadays we believe the value of S results from baryon-violating processes in the early Universe – possibly at the GUT epoch around 10^{-34} s after the Big Bang. However, in most GUT models, S is predicted to be of order α^{-n} , where n is an integer, so the anthropic constraint $S < \alpha_G^{-1/4}$ merely translates into the constraint $\alpha_G < \alpha^{4n}$. If $n=5$, this just gives the convective star condition [14]. An interesting twist on these arguments has been provided by Aguirre [15], who describes anthropic constraints on ‘cold’ cosmological models (i.e. models with an initial photon-to-baryon ratio much smaller than currently observed). He points out that such models could provide life-supporting conditions with very different values of the cosmological parameters.
- We gave no anthropic constraints on the cosmological constant Λ since this was assumed to be zero, perhaps for fundamental physical reasons. Nowadays, observations indicate that the cosmic expansion is accelerating, and this may be attributed to a positive cosmological constant. Indeed, there is a remarkable coincidence in that the vacuum and matter densities are comparable at the present epoch, even though their ratio is strongly time-dependent. As first emphasized by Weinberg [16] and later studied by Efstathiou [17] and Vilenkin [18], this may provide the strongest anthropic fine-tuning of all, since *a priori* Λ could be 120 orders of magnitude larger than observed. This is because the growth of density perturbations is quenched once Λ dominates the cosmological density, so if bound systems have not formed by then, they never will. The precise form of the anthropic upper limit on Λ depends on the amplitude of the density fluctuations, Q , and has been discussed by Tegmark and Rees [19]. These arguments have recently been refined [20, 21]. It should be stressed that a cosmological constant is not the only possible explanation for the cosmic

acceleration. An alternative explanation is to invoke ‘dark energy’ in the form of a scalar field – termed ‘quintessence’ [22] – and this may better explain the near-equality of the vacuum and matter densities. However, some anthropic fine-tuning may be required even in this case [23].

- Various other anthropic constraints have been investigated since my 1979 paper with Rees, and some of these are discussed in this volume. For example, the existence of dark matter has been much more firmly established and this is now known to have about 25% of the total cosmological density. There are still many possible dark matter candidates, but most of them have been associated with such constraints. For example, if WIMPs provide the dark matter, then their density will be comparable to the baryon density provided the aforementioned relationship $\alpha_G \sim \alpha_W^4$ is satisfied [24]. If axions provide the dark matter, then anthropic arguments again explain why their density is comparable with the baryon density, providing the strong CP-violating factor θ (associated with Peccei–Quinn symmetry-breaking at a time of order 10^{-30} s) varies across the different inflationary domains [25].

The crucial role of these fine-tunings in the evolution of the Universe is summarized in Table 5.1. This summarizes the times of various key steps in the history of the Big Bang and indicates the various anthropic fine-tunings associated with each of them. The times are expressed logarithmically in seconds and the quantities appearing under the heading ‘Condition’ are defined in the text.

Table 5.1. *Cosmological anthropic constraints*

log(t/s)	Event	Condition	Anthropic significance
+17.5	present epoch	$\Omega < 10$	else premature recollapse
+17.0	planet formation	$\alpha_G > \alpha^{20}$	need convective stars
+16.5	star formation	$\alpha_G \sim \alpha_W^4$	need supernovae
		$\alpha_G < \alpha^{20}$	need radiative stars
		$ \Delta\alpha_S < 0.005\alpha_S$	need triple-alpha resonance
+16	galaxy formation	$\Omega > 0.1, \Omega_\Lambda < 1$	overdense regions must bind
+11	end of radiation era	$S < \alpha_G^{-1/4}$	must precede galaxy formation
+2	Big Bang	$\alpha_G < \alpha_W^4$	else all hydrogen goes to helium
	nucleosynthesis	$\Delta\alpha_S < 0.02\alpha_S$	else all hydrogen goes to diprotons
		$\Delta\alpha_S > 0.02\alpha_S$	else deuterons unbound
−30	axion production	$\theta \ll 1$	need enough baryons
−34	baryosynthesis	$\alpha_G > \alpha^{4n}$	need enough photons
−35	inflation	$V'' \ll V$	need enough inflation

5.3 Universe or multiverse?

Although the status of the anthropic constraints involving cosmological parameters was not completely clear in 1979, the anthropic relationships involving the parameters of fundamental physics were certainly not predicted by any theories at the time and this remains the case today. Even if such relationships do transpire to be predicted by some ‘final theory’, it would be remarkable that the theory should yield exactly the coincidences required for life. One must therefore turn to more radical interpretations of these coincidences.

The first possibility is that the coincidences reflect the existence of a ‘beneficent being’ who tailor-made the Universe for our benefit. Such an interpretation is logically possible and appeals to theologians [26]. Indeed, some people now use the term ‘Strong Anthropic Principle’ to imply that the Universe was created with the *purpose* of creating life. However, Rees and I certainly did not have this teleological interpretation in mind at the time of our paper. In any case, most physicists are uncomfortable with this interpretation.

Another possibility, proposed by Wheeler [27], is that the Universe does not properly *exist* until consciousness has arisen. This is based on the notion that the Universe is described by a quantum mechanical wave-function and that consciousness is required to collapse this wave-function. Once the Universe has evolved consciousness, one might think of it as reflecting back on its Big Bang origin, thereby forming a closed circuit which brings the world into existence. Even if consciousness really does collapse the wave-function (which is far from certain), this explanation is also somewhat metaphysical.

The third possibility (and the one that is the focus of this book) is that there is not just one universe but a large ensemble of them, all with different (possibly random) coupling constants. As mentioned in Chapter 1 and reviewed in more detail by Tegmark [28], there are many versions of the multiverse proposal. Not all of these necessarily entail a variation in the physical constants across the ensemble. Therefore, as stressed by Rees [29, 30], a key issue in assessing the multiverse proposal is whether some of the physical constants are contingent on accidental features of symmetry-breaking and the initial conditions of our universe, or whether the future ‘Theory of Everything’ will determine all of them uniquely.

In the first case, there would be room for the Anthropic Principle and one could envisage the Universe as occupying a point in some multi-dimensional space of coupling constants. In the second case, there would be no room for the Anthropic Principle and any fine-tunings would have to be regarded

as coincidental. (The only way out, as emphasized by Tegmark [28], would be to consider worlds with different physical laws or different mathematical foundations and argue that only some of these can permit anthropic relationships.) There might in principle be other universes in the second case, but they would all have the same values for the constants, so there would be little point in invoking them. Therefore the two cases correspond essentially to the multiverse and single universe options, respectively.

If one grants the existence of a multiverse, the question then arises of whether our universe is typical or atypical within the ensemble. Anthropic advocates usually assume that life-forms similar to our own will be possible in only a tiny subset of universes. More general life-forms may be possible in a somewhat larger subset (e.g. if one envisages cold cosmological models of the kind discussed by Aguirre [15]), but life will not be possible everywhere. One may not have the *same* anthropic relation in every universe, but one will have *some* relation.

On the other hand, by invoking a Copernican perspective, Smolin has argued that *most* of the universes should have properties like our own, so that ours is typical. His own approach invokes a form of cosmological natural selection; the formation of black holes is supposed to generate new baby universes in which the constants are slightly mutated [31, 32]. In this way, after many generations, the parameter distribution will be peaked around those values for which black hole formation is maximized. This proposal involves very speculative physics, since we have no understanding of how the baby universes are born, but it has the virtue of being *testable* since one can calculate how many black holes would form if the parameters were different. Note that Smolin's proposal makes no reference to observers, so it would not be regarded as anthropic in the usual sense of the term.

A new twist arises if the (so-called) constants vary in time, even in our universe. This is expected in some higher-dimensional theories since the constants should be related to the size of the compact dimensions and this would be expected to change during at least part of the universe's history. Recently, some astronomers claim to have found positive evidence for a variation in α – of about seven parts in a million – by studying absorption lines in several hundred quasars [33]. If so, one might also expect the relationship $m_e/m_p \sim 10\alpha^2$ to imply that the electron–proton mass ratio varies, and there may indeed be evidence for this as well. Sandvik and colleagues attempt to model this effect and suggest that α should remain constant during both the early radiation-dominated phase of the universe and late curvature-dominated or Λ -dominated phases [34]. However, it could still vary over the intermediate matter-dominated phase, and this would make it

difficult to satisfy the anthropic constraints on α for an extended period if the curvature or cosmological constant were very small.

At first sight, this suggests that a variation in the coupling constants would make the anthropic constraints harder to understand. However, it is interesting that the brane cosmology paradigm (discussed in Chapter 1) may provide a natural explanation for the sort of power-law relations between the coupling constants which arise in the anthropic arguments. This is because the variation in the gravitational coupling constant would be associated with the change in the bulk volume, whereas the variation in the other coupling constants would be associated with the change in the volume of the brane or some manifold of intermediate dimensionality. In this case, relationships like $\alpha_G \sim \alpha_W^4 \sim \alpha^{20}$ could just reflect the relative number of internal and external dimensions, so these could themselves be constrained anthropically.

Many contributors to this volume consider whether the multiverse proposal can be tested and ask how legitimate it is to invoke the existence of other universes for which there may never be any direct evidence? Lee Smolin stresses [35] that the multiverse proposal is legitimate only if one has a theory which independently predicts it and that such a theory, to be scientific, must be falsifiable. He argues very forcefully that the notion of a multiverse is neither falsifiable nor testable. However, not everybody concedes this point. For example, Rees points out [36] that one way of testing the multiverse proposal is to calculate the probability distribution for various parameters across the different universes. In particular, if the distribution for the amplitude of the density fluctuations fell off too slowly, we would be surprised to be in a universe with a value as small as that observed.

5.4 How do we interpret the anthropic coincidences?

Even if one accepts that a multiverse exists and – contrary to Smolin’s picture – gives rise to anthropic selection effects, there is still considerable ambiguity in how one interprets this. What determines the selection, or, more precisely, what qualifies as an observer? Is it just human beings, or life in general? Is some minimum threshold of intelligence required, or does the mere existence of consciousness suffice? In addressing these questions, I will necessarily veer into more philosophical domains.

As mentioned earlier, although ‘anthropos’ is the Greek word for ‘man’, the arguments have nothing to do with humans in particular. Indeed, Brandon Carter (who coined the term) admits that its introduction was unfortunate. Therefore anthropic arguments do not necessarily enhance the status of human beings or support the religious view that we have a special

role in the Universe. This interpretation may still be possible if humans turn out to be the only form of life in the Universe. In this context, it is interesting that Carter has argued that we may be the only site of life within our cosmological horizon [37]. He infers this from the remarkable coincidence that the time for life to arise on Earth seems to have been comparable to the cosmological time.

Even if this were true, most cosmologists would still be reluctant to attribute great significance to humans in particular. Therefore it is more traditional to associate the anthropic constraints with life in general. In fact, Davies explicitly associates them with a ‘life principle’ [38]. Until recently, science would have regarded the existence of life as an incidental rather than fundamental feature of the Universe. Indeed, in the nineteenth century, the second law of thermodynamics was taken to imply that the Universe must eventually undergo a ‘heat death’, with life and all other forms of order inevitably deteriorating. However, recent developments in cosmology have led to a reversal of this view. According to the Big Bang theory, the history of the Universe reveals an increasing rather than decreasing degree of organization, and modern physics – without any recourse to divine intervention and without any violation of the second law of thermodynamics – is able to explain this. Heat death is avoided because local pockets of order can be purchased at the expense of a global increase in entropy, and, if the Universe continues to expand forever, intelligent beings may be able to delay their disintegration indefinitely [39].

Some of the types of organization which exist in the Universe are summarized in the so-called ‘Pyramid of Complexity’, introduced by Reeves [40] and reproduced in Fig. 5.1. This shows the different levels of structure as one goes from quarks to nucleons to atoms to simple molecules to biomolecules to cells and finally to living organisms. This hierarchy of structure reflects the existence of the strong force at the lower levels and the electric force at the higher ones. As one ascends the pyramid, the structures become more complex – so that the number of different patterns becomes larger – but they also become more fragile. The pyramid becomes narrower as one rises, and this reflects the fact that the fraction of matter incorporated into the objects decreases as the degree of organization increases.

The Big Bang theory explains *when* these structures arise because the Pyramid of Complexity only emerges as the Universe expands and cools. At early times, the Universe is mainly in the form of quarks. Neutrons and protons appear at a few microseconds, light nuclei at several minutes, atoms at a million years, and – following the formation of stars and planets – molecules and cells at ten billion years. The Big Bang theory also explains

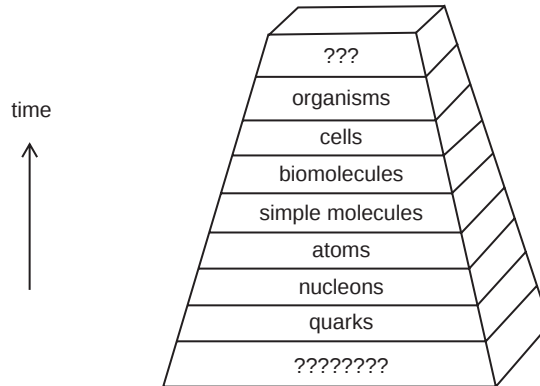


Fig. 5.1. Summary of the different levels of structure which exist in the Universe and how this has arisen during the Big Bang.

why the pyramid came about. The key point is that structures arise because processes cannot occur fast enough in an expanding universe to maintain equilibrium. If it had its way, each type of force would always form the objects which are most stable from its own perspective (e.g. the strong force would turn all nuclei into iron; the electric force would turn all atoms into noble gases; and gravity would turn all matter into black holes). However, all variety would be lost if this were the case, and it is only the disequilibrium entailed by the rapid expansion of the Universe which prevents this.

For example, the reason all nucleons do not go into iron as a result of cosmological nucleosynthesis is that the Universe is expanding too fast for most nuclei to interact with each other at this time. The reason gravity does not turn all stars into black holes is because the pressure associated with nuclear energy release and eventually quantum effects support them against gravity. The forces may eventually attain their goal, but only after an enormous length of time and, even then, only for a limited period. (For example, if the Universe exists long enough, everything may eventually end up in black holes, but on a still longer timescale these black holes will evaporate into radiation.) As emphasized in Table 5.1, it is only the anthropic fine-tuning of the coupling constants that allows the ascension of the lower levels of the pyramid. Therefore, the Pyramid of Complexity can only arise in a small subset of the ensemble of universes.

Note that there is an important difference between the structures which exist at the top and the bottom of the pyramid. Those at the bottom are stable and need large amounts of energy to destroy them, while those at the top must be constantly maintained by exchanging energy with the outside world. More precisely, they must extract information from the world, and

the second law of thermodynamics requires that this process is inevitably accompanied by the release of entropy. A store of information arises whenever there exists a source of entropy which has not been released by previous processes. For example, nuclear information is contained in nuclei other than iron, and this can be extracted by nuclear burning inside the Sun, the ultimate source and sustainer of all life-forms on Earth. Similarly, living organisms can feed on plants, and humans can exploit fossil fuels, because these things contain complex molecules with consumable electromagnetic information. Thus there is an inevitable link between complexity and life, and the key to this link is *information*.

Another crucial ingredient at the top level of the pyramid is competitiveness. This is a vital factor in evolution because, as a population grows, the competition for food leads to predation and increasingly sophisticated survival strategies. The proliferation of life-forms due to mutation plays a crucial role in this process. Different modes of perception and motor activity are also required, and this leads to the development of organisms with a central nervous system. From this perspective, brains – certainly the most complex structures on Earth – are merely data integration systems, and the main purpose of intelligence is to increase survival efficiency. Minds, of course, might be regarded as the ultimate storers and extractors of information.

Figure 5.1 suggests that the anthropic fine-tunings are more related to the emergence of complexity than life or minds; they could equally well be regarded as prerequisites for inanimate objects such as motor cars or TV sets. However, here on Earth at least, the development of minds seems to have occurred relatively quickly once the first signs of life arose, so it is conceivable that this applies more generally. Provided there are no extra ‘biological’ fine-tunings required for the higher levels of the pyramid to arise, the evolution of complexity may inevitably (and fairly rapidly) lead to life and consciousness. In this case, the distinction between life and complexity is not so clear-cut. The former is just a particular realization of the latter and may naturally emerge from it. Therefore the question of what constitutes an observer may be rather incidental. Complexity appears to be the key, and that encompasses everything. From this perspective, the term ‘Complexity Principle’ would be preferable to ‘Anthropic Principle’.

References

- [1] J. D. Barrow and F. J. Tipler. *The Anthropic Cosmological Principle* (Oxford: Oxford University Press, 1986).
- [2] R. H. Dicke. *Nature*, **192** (1961), 440.
- [3] A. J. M. Garret and P. Coles. *Comments Astrophys.* **17** (1993), 23.

- [4] B. J. Carr and M. J. Rees. *Nature*, **278** (1979), 605.
- [5] B. Carter. In *Confrontation of Cosmological Models with Observations*, ed. M. S. Longair (Dordrecht: Reidel, 1974), pp. 291–298.
- [6] D. N. Page [hep-th/0203051].
- [7] F. Hoyle. *Astrophys. J.* **118** (1953), 513.
- [8] H. Oberhummer, A. Csoto and H. Schlattl. *Science*, **289** (2000), 88.
- [9] C. J. Hogan. *Rev. Mod. Phys.* **72** (2000), 1149.
- [10] A. H. Guth. *Phys. Rev. D* **23** (1981), 347.
- [11] D. N. Spergel, L. Verde, H. V. Peiris *et al.* *Astrophys. J. Supp.* **148** (2003), 175.
- [12] A. D. Linde. *Particle Physics and Inflationary Cosmology* (Chur, Switzerland: Harwood, 1990).
- [13] S. W. Hawking. This volume (2007).
- [14] B. J. Carr. *J. Brit. Interplan. Soc.* **44** (1991), 63.
- [15] A. Aguirre. *Phys. Rev. D* **64** (2001), 83508.
- [16] S. Weinberg. *Rev. Mod. Phys.* **61** (1989), 1.
- [17] G. Efstathiou. *Mon. Not. Roy. Astron. Soc.* **274** (1995), L73.
- [18] A. Vilenkin. *Phys. Rev. Lett.* **74** (1995), 846.
- [19] M. Tegmark and M. J. Rees. *Astrophys. J.* **499** (1998), 526.
- [20] M. Tegmark. *Ann. Phys.* **270** (1998), 1.
- [21] M. Tegmark. In *Science and Ultimate Reality*, eds. J. D. Barrow, P. C. W. Davies and C. L. Harper (Cambridge: Cambridge University Press, 2004).
- [22] P. J. Steinhardt and N. Turok. *Science* **296** (2002), 1436.
- [23] R. Kallosh and A. Linde. *Phys. Rev. D* **67** (2003), 023510.
- [24] M. S. Turner and B. J. Carr. *Mod. Phys. Lett. A* **2** (1987), 1.
- [25] F. Wilczek. This volume (2007).
- [26] J. Polkinghorne. *The Faith of a Physicist* (Princeton, NJ: Princeton University Press, 1994).
- [27] J. Wheeler. In *Foundational Problems in the Special Sciences*, eds. R. Butts and J. Hintikka (Dordrecht: Reidel, 1977), p. 3.
- [28] M. Tegmark. *Ann. Phys.* **270** (1998), 1.
- [29] M. J. Rees. *Our Cosmic Habitat* (Princeton, NJ: Princeton University Press, 2001).
- [30] M. J. Rees. *Just Six Numbers: The Deep Forces that Shape the Universe* (London: Weidenfeld and Nicholson, 1999).
- [31] L. Smolin. *Class. Quant. Grav.* **9** (1992), 173.
- [32] L. Smolin. *The Life of the Cosmos* (Oxford: Oxford University Press, 1997).
- [33] J. K. Webb, M. T. Murphy, V. V. Flambaum *et al.* *Phys. Rev. Lett.* **87** (2001), 091301.
- [34] H. B. Sandvik, J. D. Barrow and J. Magueijo. *Phys. Rev. Lett.* **88** (2002), 031302.
- [35] L. Smolin. This volume (2007).
- [36] M. J. Rees. This volume (2007).
- [37] B. Carter. *Phil. Trans. Roy. Soc. A* **310** (1983), 347.
- [38] P. C. W. Davies. This volume (2007).
- [39] F. Dyson. *Rev. Mod. Phys.* **51** (1979), 447.
- [40] H. Reeves. *The Hour of Our Delight* (New York: W. H. Freeman, 1991).

6

Cosmology from the top down

S. W. Hawking

Centre for Mathematical Sciences, University of Cambridge

6.1 Problems with bottom-up approach

The usual approach in physics could be described as building from the bottom up. That is, one assumes some initial state for a system and then evolves it forward in time with the Hamiltonian and the Schrödinger equation. This approach is appropriate for laboratory experiments like particle scattering, where one can prepare the initial state and measure the final state. The bottom-up approach is more problematic in cosmology, however, because we do not know what the initial state of the Universe was, and we certainly cannot try out different initial states and see what kinds of universe they produce.

Different physicists react to this difficulty in different ways. Some – generally those brought up in the particle physics tradition – just ignore the problem. They feel the task of physics is to predict what happens in the laboratory, and they are convinced that string theory or M-theory can do this. All they think remains to be done is to identify a solution of M-theory, a Calabi–Yau or G2 manifold that will give the Standard Model as an effective theory in four dimensions. But they have no idea why the Universe should be 4-dimensional and have the Standard Model, with the values of the forty or so parameters that we observe. How can anyone believe that something so messy is the unique prediction of string theory? It amazes me that people can have such blinkered vision – that they can concentrate just on the final state of the Universe and not ask how and why it got there.

Those physicists that try to explain the Universe from the bottom up mostly belong to one of two schools, these being associated with either the inflationary or pre-big-bang scenarios. I now discuss these approaches in turn and show that neither of them is satisfactory.

Universe or Multiverse?, ed. Bernard Carr. Published by Cambridge University Press.
© Cambridge University Press 2007.

6.1.1 Inflationary scenarios

In the case of inflation, the idea is that the exponential expansion obliterates the dependence on the initial conditions [1], so we would not need to know exactly how the Universe began – just that it was inflating. To lose all memory of the initial state would require an infinite amount of exponential expansion, which leads to the notion of ever-lasting or eternal inflation [2, 3]. The original argument for eternal inflation went as follows. Consider a massive scalar field in a spatially infinite expanding universe. Suppose the field is nearly constant over several horizon regions on a spacelike surface. In an infinite universe, there will always be such regions. The scalar field will have quantum fluctuations. In half the regions, the fluctuations will increase the field; in the other half, they will decrease it. In the half where the field jumps up, the extra energy density will cause the universe to expand faster than in the half where the field jumps down. After a certain proper time, more than half the regions will have the higher value of the field, because the high-field regions will expand faster than the low-field regions.

Thus the volume-averaged value of the field will rise. There will always be regions of the universe in which the scalar field is high, so inflation is eternal. The regions in which the scalar field fluctuates downwards will branch off from the eternally inflating region and exit inflation. Because there will be an infinite number of exiting regions, advocates of eternal inflation get themselves tied in knots on what a typical observer would see. So even if eternal inflation worked, it would not explain *why* the Universe is the way it is.

In fact, the argument for eternal inflation that I have outlined has serious flaws. First, it is not gauge-invariant. If one takes the time surfaces to be surfaces of constant volume increase rather than surfaces of constant proper time, the volume-averaged scalar field does not increase. Second, it is not consistent. The equation relating the expansion rate to the energy density is an integral of motion. Neither side of the equation can fluctuate because energy is conserved. Third, it is not covariant. It is based on a $3 + 1$ split. From a 4-dimensional view, eternal inflation can only be de Sitter space with bubbles. The energy-momentum tensor of the fluctuations in a single scalar field is not large enough to support a de Sitter space, except possibly at the Planck scale, where everything breaks down. For these reasons – lack of gauge-invariance and covariance and inconsistency – I do not believe the usual argument for eternal inflation. However, as I shall explain later, I think the Universe may have had an initial de Sitter stage considerably longer than the Planck timescale.

6.1.2 *Pre-big-bang scenarios*

I now turn to pre-big-bang scenarios, which are the main alternative to inflation. I shall take them to include the ekpyrotic [4] and cyclic models [5], as well as the older pre-big-bang model [6]. The observations of the microwave background fluctuations show that there are correlations on scales larger than the horizon size at decoupling. These correlations could be explained if there had been inflation, because the exponential expansion would have meant that regions that are now widely separated were once in causal contact with each other. On the other hand, if there were no inflation, the correlations must have been present at the beginning of the expansion of the Universe. Presumably, they arose in a previous contracting phase and somehow survived the singularity or brane collision.

It is not clear if effects can be transmitted through a singularity, or if they will produce the right signature in the microwave background fluctuations. But even if the answer to both of these questions is yes, the pre-big-bang scenarios do not answer the central question of cosmology: why is the Universe the way it is? All the pre-big-bang scenarios can do is shift the problem of the initial state from 13.7 Gy ago to the infinite past. But a boundary condition is a boundary condition, even if the boundary is at infinity. The present state of the Universe would depend on the boundary condition in the infinite past. The trouble is, there is no natural boundary condition, such as the Universe being in its ground state. The Universe does not have a ground state. It is unstable and is either expanding or contracting. The lack of a preferred initial state in the infinite past means that pre-big-bang scenarios are no better at explaining the Universe than supposing that someone wound up the clock and set the Universe going at the big bang.

6.2 Sum over histories

The bottom-up approach to cosmology – supposing some initial state and evolving it forward in time – is basically classical, because it assumes that the Universe began in a way that was well defined and unique. But one of the first acts of my research career was to show with Roger Penrose that any reasonable classical cosmological solution has a singularity in the past [7]. This implies that the origin of the Universe was a quantum event. This means that it should be described by the Feynman ‘sum over histories’. The Universe does not have just a single history, but every possible history, whether or not they satisfy the field equations. Some people make a great mystery of the ‘many worlds’ interpretation of quantum theory, but to me these are just different expressions of the Feynman path integral.

One can use the path integral to calculate the quantum amplitudes for observables at the present time. The wave-function of the Universe, or amplitude for the metric h_{ij} on a surface S of co-dimension one, is given by a path integral over all metrics, g , that have S as a boundary. Normally, one thinks of path integrals as having two boundaries: an initial surface and a final one. This would be appropriate in a proper quantum treatment of a pre-big-bang scenario, like the ekpyrotic model. In this case, the initial surface would be in the infinite past.

But there are two big objections to the path integral for the Universe having an initial surface. The first is the G question (i.e. the issue of whether one needs God). What was the initial state of the Universe and why was it like that? As I said earlier, there does not seem to be a natural choice for the initial state. It cannot be flat space since that would remain flat space.

The second objection is equally fundamental. In most models, the quantum state on the final surface will be independent of the state on the initial one. This is because there will be metrics in which the initial surface is in one component and the final surface is in a separate, disconnected component of the 4-dimensional manifold. Such metrics will exist in the Euclidean regime. They correspond to the quantum annihilation of one universe and the quantum creation of another. This would not be possible if there were something that was conserved that propagated from the initial surface to the final surface. But the trend in cosmology in recent years has been to claim that the Universe has no conserved quantities. Things like baryon number are supposed to have been created by grand unified or electro-weak theories, together with CP violation. So there is no way one can rule out the final surface from belonging to a different universe than the initial surface. In fact, because there are so many different possible universes, they will dominate and the final state will be independent of the initial state. It will be given by a path integral over all metrics whose only boundary is the final surface. In other words, it is the so-called ‘no boundary’ quantum state [8].

6.3 Top-down approach

If one accepts that the no boundary proposal is the natural prescription for the quantum state of the Universe, one is led to a profoundly different view of cosmology and the relationship between cause and effect. One should not follow the history of the Universe from the bottom up, because that assumes there is a single history, with a well defined starting point and evolution. Instead, one should trace the histories from the top down – in other

words, backwards from the measurement surface, S , at the present time. The histories that contribute to the path integral do not have an independent existence, but depend on the amplitude that is being measured. As an example of this, consider the apparent dimension of the Universe. The usual idea is that spacetime is a 4-dimensional nearly flat metric cross a small 6- or 7-dimensional internal manifold. But why are there not more large dimensions? Why are any dimensions compactified? There are good reasons to think that life is possible only in four dimensions, but most physicists are very reluctant to appeal to the anthropic principle. They would rather believe that there is some mechanism that causes all but four of the dimensions to compactify spontaneously. Alternatively, maybe all dimensions started small, but for some reason four dimensions expanded and the rest did not.

I am sorry to disappoint these hopes, but I do not think there is a dynamical reason for the Universe to appear 4-dimensional. Instead, the no boundary proposal predicts a quantum amplitude for every number of large spatial dimensions from 0 to 10. There will be an amplitude for the Universe to be eleven-dimensional Minkowski space, i.e. with ten large spatial dimensions. However, the value of this amplitude is of no significance, because we do not live in eleven dimensions. We are not asking for the probabilities of various dimensions for the Universe. As long as the amplitude for three large spatial dimensions is not exactly zero, it does not matter how small it is compared with that for other numbers of dimensions. The Universe appears to be 4-dimensional, so we are interested only in amplitudes for surfaces with three large dimensions. This may sound like the anthropic principle argument that the reason we observe the Universe to be 4-dimensional is that life is possible only in four dimensions. But the argument here is different, because it does not depend on whether four dimensions is the only arena for life. Rather, it is that the probability distribution over dimensions is irrelevant, because we have already measured that we are in four dimensions.

The situation with the low energy effective theory of particle interactions is similar. Many physicists believe that string theory will uniquely predict the Standard Model and the values of its forty or so parameters. The bottom-up picture would be that the Universe begins with some grand unified symmetry, like $E_8 \times E_8$. As the Universe expanded and cooled, the symmetry would break to the Standard Model, maybe through intermediate stages. The hope would be that string theory would predict the pattern of symmetry-breaking, the masses of particles, couplings and mixing angles. However, personally I find it difficult to believe that the Standard Model is

the unique prediction of fundamental theory. It is so ugly and the mixing angles etc. seem accidental rather than part of a grand design.

In string/M-theory, low energy particle physics is determined by the internal space. It is well known that M-theory has solutions with many different internal spaces. If one builds the history of the Universe from the bottom up, there is no reason it should end up with the internal space for the Standard Model. However, if one asks for the amplitude for a spacelike surface with a given internal space, one is interested only in those histories which end with that internal space. One therefore has to trace the histories from the top down, backwards from the final surface.

One can calculate the amplitude for the internal space of the Standard Model on the basis of the ‘no boundary’ proposal. As with the dimensionality, it does not matter how small this amplitude is relative to other possibilities. It would be like asking for the amplitude that I am Chinese. I know I am British, even though there are more Chinese. Similarly, we know the low energy theory is the Standard Model, even though other theories may have a larger amplitude.

Although the relative amplitudes for radically different geometries do not matter, those for neighbouring geometries are important. For example, the fluctuations in the microwave background correspond to differences in the amplitudes for spacelike surfaces that are small perturbations of flat 3-space cross the internal space. It is a robust prediction of inflation that the fluctuations are Gaussian and nearly scale-independent. This has been confirmed by the recent observations by the WMAP satellite [9]. However, the predicted amplitude is model-dependent.

The parameters of the Standard Model will be determined by the moduli of the internal space. Because they are moduli at the classical level, their amplitudes will have a fairly flat distribution. This means that M-theory cannot predict the parameters of the Standard Model. Obviously, the values of the parameters we measure must be compatible with the development of life. I hesitate to say ‘intelligent’ life, but – within the anthropically allowed range – the parameters can have any values. So much for string theory predicting the fine-structure constant. However, although the theory cannot predict the value of the fine-structure constant, it *will* predict that it should have spatial variations, like the microwave background. This would be an observational test of our ideas of M-theory compactification.

How can one get a non-zero amplitude for the present state of the Universe if, as I claim, the metrics in the path integral have no boundary apart from the surface at the present time? I cannot claim to have the definitive answer, but one possibility would be if the 4-dimensional part of the metric went

back to a de Sitter phase. Such a scenario is realized in trace-anomaly driven inflation, for example [10]. In the Lorentzian regime, the de Sitter phase would extend back into the infinite past. It would represent a universe that contracted to a minimum radius and then expanded again. But we know that Lorentzian de Sitter can be closed off in the past by half the 4-sphere. One can interpret this in the bottom-up picture as the spontaneous creation of an inflating universe from nothing. Some pre-big-bang or ekpyrotic scenarios, involving collapsing and expanding universes, can probably be formulated in no boundary terms with an orbifold point. However, this would remove the scale-free perturbations which, it is claimed, develop during the collapse and carry on into the expansion. So again it is a ‘no no’ for pre-big-bang and ekpyrotic universes.

6.4 Conclusions

In conclusion, the bottom-up approach to cosmology would be appropriate if one knew that the Universe was set going in a particular way, in either the finite or infinite past. However, in the absence of such knowledge, it is better to work from the top down, by tracing backwards from the final surface the histories that contribute to the path integral. This means that the histories of the Universe depend on what is being measured, contrary to the usual idea that the Universe has an objective, observer-independent, history. The Feynman path integral allows every possible history for the Universe, and the observations select out the sub-class of histories that have the property that is being observed. There are histories in which the Universe eternally inflates or is 11-dimensional, but they do not contribute to the amplitudes we measure. I would call this the ‘selection principle’ rather than the ‘anthropic principle’ because it does not depend on intelligent life. Life may, after all, be possible in eleven dimensions, but we know we live in four.

The results are disappointing for those who hoped that the ultimate theory would predict everyday physics. We cannot predict discrete features such as the number of large dimensions or the gauge symmetry of the low energy theory. Rather, we use them to select which histories contribute to the path integral. The situation is better with continuous quantities, such as the temperature of the cosmic microwave background or the parameters of the Standard Model. We cannot measure their probability distributions, because we have only one value for each quantity. We cannot tell whether the Universe was likely to have the values we observe, or whether it was just a lucky chance. However, it is noteworthy that the parameters we measure seem to lie in the interior of the anthropically allowed range rather than

at the edge. This suggests that the probability distribution is fairly flat – not like the exponential dependence on the density parameter, Ω , in the open inflation model that Neil Turok and I proposed [11]. In that model, Ω would have had the minimum value required to form a single galaxy, which is all that is anthropically necessary. All the other galaxies which we see are superfluous.

Although the theory advocated here cannot predict the average values of these quantities, it will predict that there will be spatial variations – such as the fluctuations in the microwave background. However, the size of these variations will probably depend on moduli or parameters that we cannot predict. So even when we understand the ultimate theory, it will not tell us much about how the Universe began. It cannot predict the dimension of spacetime, the gauge group or other parameters of the low energy effective theory. On the other hand, the theory will predict that the total energy density will be exactly the critical one, though it will not determine how this energy is divided between conventional matter and a cosmological constant or quintessence. The theory will also predict a nearly scale-free spectrum of fluctuations, but it will not determine the amplitude.

So, to come back to the question with which I began this chapter: does string theory predict the state of the Universe? The answer is that it does not. It allows a vast landscape of possible universes in which we occupy an anthropically permitted location [12]. But I feel we could have selected a better neighbourhood.

References

- [1] A. H. Guth. *Phys. Rev. D* **23** (1981), 347.
- [2] A. Vilenkin. *Phys. Lett. D* **27** (1983), 2848.
- [3] A. D. Linde. *Phys. Lett. B* **175** (1986), 395.
- [4] J. Khoury, B. A. Ovrut, P. J. Steinhardt and N. Turok. *Phys. Rev. D* **61** (2001), 123522.
- [5] P. J. Steinhardt and N. Turok. *Phys. Rev. D* **65** (2002), 126003.
- [6] M. Gasperini, M. Maggiore and G. Veneziano. *Nucl. Phys. B* **494** (1997), 315.
- [7] S. W. Hawking and R. Penrose. *Proc. Roy. Soc. Lond. A* **314** (1970), 529.
- [8] J. Hartle and S. W. Hawking. *Phys. Rev. D* **28** (1983), 2960.
- [9] D. N. Spergel, L. Verde, H. V. Peiris *et al.* *Astrophys. J. Suppl.* **148** (2003), 175.
- [10] S. W. Hawking, T. Hertog and H. S. Reall. *Phys. Rev. D* **63** (2001), 083504.
- [11] S. W. Hawking and N. Turok. *Phys. Lett. B* **425** (1998), 25.
- [12] L. Susskind. This volume (2007) [hep-th/0302219].

7

The multiverse hierarchy

Max Tegmark

Department of Physics, Massachusetts Institute of Technology

7.1 Introduction

Parallel universes are now all the rage, cropping up in books, movies and even jokes: ‘You passed your exam in many parallel universes – but not this one.’ However, they are as controversial as they are popular, so it is important to ask whether they are within the purview of science or merely silly speculation. They are also a source of confusion, since many people fail to distinguish between the different types of parallel universes proposed.

In the big bang model, the farthest one can observe is the distance that light has travelled during the 14 billion years since the expansion began. The most distant visible objects are now about 4×10^{26} m away.¹ A sphere of this radius defines our observable universe or our *horizon volume*. We will sometimes loosely refer to this as ‘our universe’, although this may be part of a region which extends much further. In this article, I will survey theories of physics involving what are termed ‘parallel universes’ or ‘multiverses’. These form a four-level hierarchy, allowing progressively greater diversity.

- **Level I** A generic prediction of cosmological inflation is an infinite ‘ergodic’ space, which contains Hubble volumes realizing all initial conditions – including one with an identical copy of you about $10^{10^{29}}$ m away.
- **Level II** Given the *fundamental* laws of physics that physicists one day hope to capture with equations on a T-shirt, different regions of space can exhibit different *effective* laws of physics (physical constants, dimensionality, particle content, etc.), corresponding to different local minima in a landscape of possibilities.

¹ After emitting the light that is now reaching us, the most distant things we can see have receded because of the cosmic expansion, and are now about 40 billion light-years away.

- **Level III** In unitary quantum mechanics, other branches of the wave-function add nothing qualitatively new, which is ironic given that this level has historically been the most controversial.
- **Level IV** Other mathematical structures give different fundamental equations of physics for that T-shirt.

The key question is therefore not *whether* there is a multiverse (since Level I is the rather uncontroversial cosmological concordance model), but rather *how many* levels it has. The different levels of the multiverse are illustrated in Fig. 7.1.

This chapter will discuss at length whether there can be evidence for other universes and whether such speculations are science or philosophy. For now, the key point to remember is that *parallel universes are not a theory, but a prediction of certain theories*. For a theory to be falsifiable, we do not need to be able to observe and test *all* its predictions, merely at least one of them. By analogy, consider Einstein’s theory of General Relativity. Because this has successfully predicted many things that we *can* observe, we also take seriously its predictions for things we *cannot* observe, for example that space continues inside a black hole event horizon and that (contrary to early misconceptions) nothing funny happens at the horizon itself. Likewise, successful predictions of the theories of cosmological inflation and unitary² quantum mechanics have made some scientists take more seriously other predictions of these theories, including various types of parallel universes. This is summarized in Table 7.1.

Let us make two cautionary remarks before delving into the details. Hubris and lack of imagination have repeatedly caused humans to underestimate the vastness of the physical world, and dismissing things merely because we cannot observe them from our vantage point is reminiscent of the ostrich with its head in the sand. Moreover, recent theoretical insights have indicated that nature may be tricking us. Einstein taught us that space is not merely a boring static void, but a dynamic entity that can stretch (the expanding universe), vibrate (gravitational waves) and curve (gravity). Searches for a unified theory also suggest that space can ‘freeze’, transitioning between different phases in a landscape of possibilities, just like water can be solid, liquid or gas. In different phases, the effective laws of physics (particles, symmetries, etc.) could vary. A fish never leaving the ocean might mistakenly conclude that the properties of water are universal, not realizing that there is also ice and steam. We may be smarter than a fish, but we

² As described below, the mathematically simplest version of quantum mechanics is ‘unitary’, lacking the controversial process known as wave-function collapse.

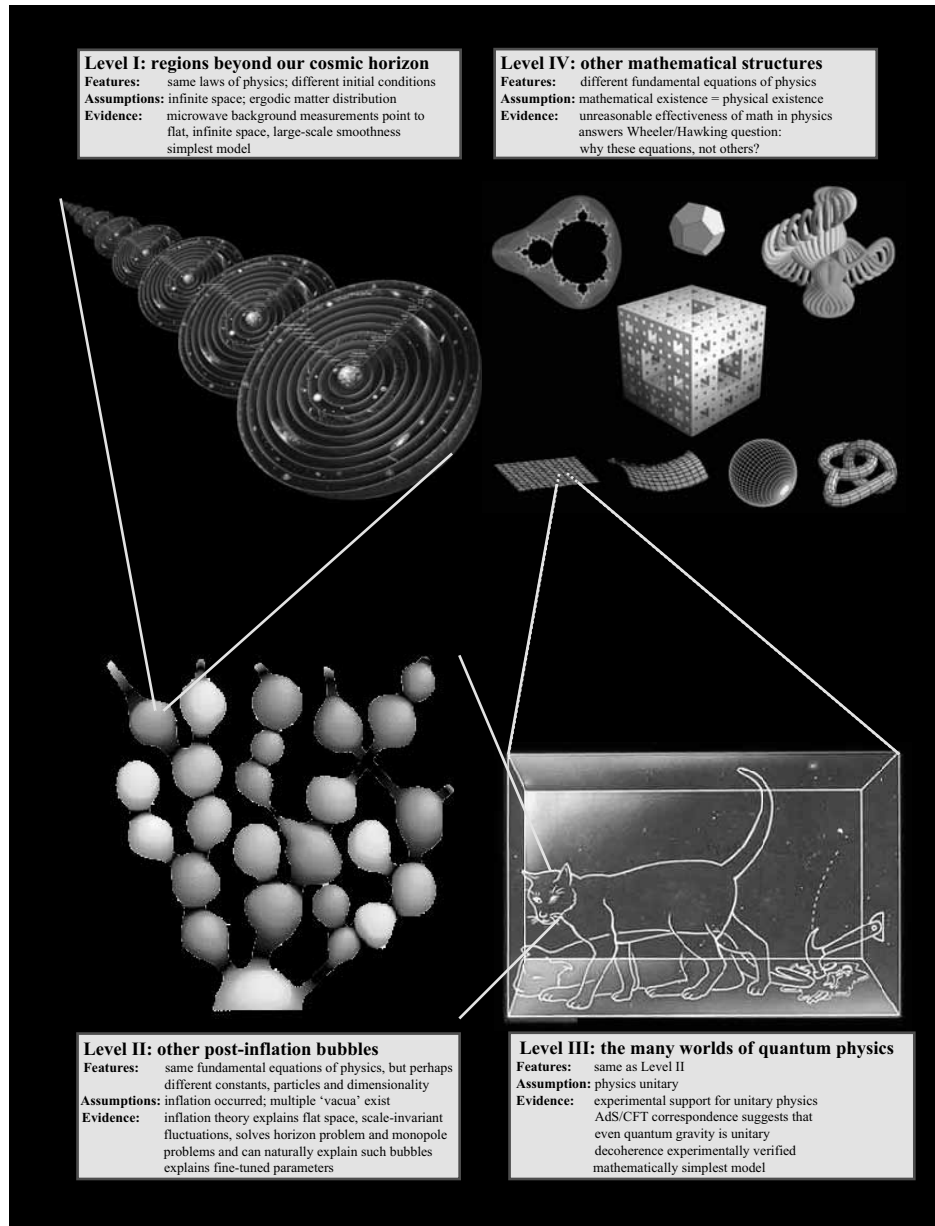


Fig. 7.1. Four different levels of multiverse.

could be similarly fooled; cosmological inflation has the deceptive property of stretching a small patch of space in a particular phase so that it fills our entire observable universe, potentially tricking us into misinterpreting our local conditions for the universal laws that should go on that T-shirt.

Table 7.1. *Theories with unobservable predictions*

Theory	Prediction
General relativity	black hole interiors
Inflation	Level I parallel universes
Unitary quantum mechanics	Level III parallel universes

7.2 Level I: regions beyond our cosmic horizon

If space is infinite and the distribution of matter is sufficiently uniform on large scales, then even the most unlikely events must take place somewhere. In particular, there are infinitely many other inhabited planets, including not just one but infinitely many copies of you – with the same appearance, name and memories. Indeed, there are infinitely many other regions the size of our observable universe, where every possible cosmic history is played out. This is the Level I multiverse.

7.2.1 Evidence for Level I parallel universes

Although the implications may seem counter-intuitive, this spatially infinite cosmological model is currently the simplest and most popular. Yet the Level I multiverse idea has been always controversial. Indeed, its proposal was one of the heresies for which the Vatican had Giordano Bruno burned at the stake in 1600. In recent times his ideas have been elaborated by various people [1–3].

Let us first review the status of the assumption of infinite space. Observationally, the lower bound on the size of space has grown dramatically, as indicated in Fig. 7.2, with no indication of an upper bound. We all accept the existence of things that we cannot see but could see if we moved or waited, such as ships beyond the horizon. Objects beyond the cosmic horizon have similar status, since the observable universe grows by a light-year every year. If anything, the Level I multiverse sounds obvious. How could space not be infinite? If space comes to an end, what lies beyond it? In fact, Einstein’s theory of gravity calls this intuition into question, since space could be finite if it has a convex curvature or an unusual topology. For example, a spherical, doughnut-shaped or pretzel-shaped universe would have a limited volume and no edges. The cosmic microwave background radiation allows sensitive tests of such scenarios, but so far the evidence is against them. Infinite models fit the data better and strong limits have been placed on the alternatives [4,5]. In addition, a spatially infinite universe is a generic prediction of the cosmological theory of inflation [2],

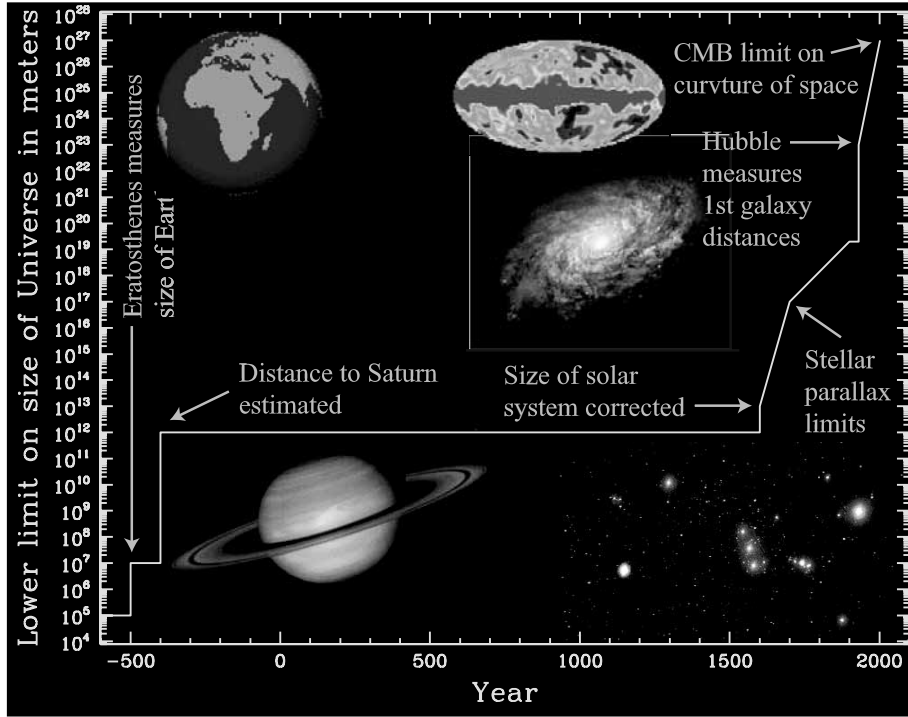


Fig. 7.2. Although an infinite universe has always been a possibility, the lower limit on the size of our universe has kept growing.

so the striking success of inflation lends further support to the idea that space is infinite.

Let us next review the status of the assumption that matter has a uniform distribution. It is possible that space is infinite, but with matter confined to a finite region around us, as in the historically popular ‘island universe’ model. In a variant on this model, matter thins out on large scales in a fractal pattern. In both cases, almost all universes in the Level I multiverse would be empty. However, recent observations of the 3-dimensional galaxy distribution and the microwave background have shown that the arrangement of matter gives way to dull uniformity on large scales, with no coherent structures larger than about 10^{24} m. Assuming that this pattern continues, space beyond our observable universe teems with galaxies, stars and planets.

7.2.2 What are Level I parallel universes like?

The physics description of the world is traditionally split into two parts: initial conditions and laws of physics specifying how these initial conditions

evolve. Observers living in parallel universes at Level I observe the same laws of physics as we do, but with different initial conditions. The currently favoured theory is that the initial conditions were created by quantum fluctuations during inflation. This generates initial conditions that are essentially random, producing density fluctuations described by an *ergodic* random field. This means that if you imagine generating an ensemble of universes, each with its own random initial conditions, then the probability distribution of outcomes in a given volume is identical to the distribution that you get by sampling different volumes in a single universe. In other words, everything that could in principle have happened here did happen somewhere else.

Inflation, in fact, generates all possible initial conditions with non-zero probability, the most likely ones being almost uniform with fluctuations at the 10^{-5} level. These were then amplified by gravitational clustering to form galaxies, stars, planets and other structures. This means that all imaginable matter configurations should occur in some Hubble volume and that we should expect our own Hubble volume to be fairly typical – at least typical among those that contain observers. A crude estimate suggests that the closest identical copy of you is about $10^{10^{29}}$ m away. About $10^{10^{91}}$ m away, there should be a sphere of radius 100 light-years identical to the one centred here, so all perceptions that we have during the next century will be identical to those of our counterparts over there. About $10^{10^{115}}$ m away, there should be an entire Hubble volume identical to ours.³

This raises an interesting philosophical point that we will reconsider later: if there are indeed many copies of ‘you’ with identical past lives and memories, you would not be able to compute your own future even if you had complete knowledge of the entire cosmos! The reason is that there is no way for you to determine which of these copies is ‘you’. Yet their lives will necessarily differ eventually, so the best you can do is predict probabilities for what you will experience from now on. This kills the traditional notion of determinism.

³ This is an extremely conservative estimate, 10^{115} being roughly the number of protons that the Pauli exclusion principle would allow you to pack into a Hubble volume at a temperature of 10^8 K. Each of these slots can be either occupied or unoccupied, giving $2^{10^{115}} \sim 10^{10^{115}}$ possibilities, so the expected distance to the nearest identical Hubble volume is $10^{10^{115}}$ Hubble radii or $10^{10^{115}}$ m. Your nearest copy is likely to be much closer than $10^{10^{29}}$ m, since the planet formation and evolutionary processes that have tipped the odds in your favour are at work everywhere. There may be 10^{20} habitable planets in our own Hubble volume alone.

7.2.3 How a multiverse theory can be tested and falsified

Is a multiverse theory one of metaphysics rather than physics? As emphasized by Karl Popper, this depends on whether the theory is empirically testable and falsifiable. Containing unobservable entities does not itself render a theory non-testable. For instance, a theory stating that there are 666 parallel universes, all of which are devoid of oxygen, makes the testable prediction that we should observe no oxygen here, and is therefore ruled out by observation.

In fact, the Level I multiverse is routinely used to rule out theories in modern cosmology, although this is rarely spelled out explicitly. For instance, cosmic microwave background (CMB) observations have recently shown that space has almost no curvature. Hot and cold spots in CMB maps have a characteristic size that depends on the curvature of space, and the observed spots appear too large to be consistent with the previously popular ‘open’ model. However, the average spot size varies randomly from one Hubble volume to another, so it is important to be statistically rigorous. When cosmologists say that the open universe model is ruled out at 99.9% confidence, they really mean that – if the open universe model were true – then fewer than one out of every 1000 Hubble volumes would show CMB spots as large as those we observe. It is inferred that the entire model (with its infinitely many Hubble volumes) is ruled out, even though we have only mapped the CMB in our own particular Hubble volume.

Thus multiverse theories *can* be tested and falsified only if they predict what the ensemble of parallel universes is and specify a probability distribution and *measure* over it. As we will see later, the measure problem can be quite serious and is still unsolved for some multiverse theories.

7.3 Level II: other post-inflation bubbles

Imagine an infinite set of distinct Level I multiverses, each represented by a bubble in Fig. 7.1, some perhaps with different dimensionality and different physical constants. We will refer to this as the Level II multiverse, and it is predicted by most currently popular models of inflation. These other domains are so far away that you would never get to them even if you travelled at the speed of light forever. The reason is that the space between our Level I multiverse and its neighbours is still undergoing inflation, which creates space faster than you can travel through it. In contrast, you could travel to an arbitrarily distant Level I universe, providing the cosmic expansion decelerates. In fact, astronomical evidence suggests that the cosmic expansion is currently accelerating and, if this acceleration continues

indefinitely, then even some Level I universes will remain forever separate. However, at least some models predict that our universe will eventually stop accelerating and perhaps even recollapse.

7.3.1 Evidence for Level II parallel universes

Inflation is an extension of the big bang theory, in which a rapid stretching of space at an early time explains why our universe is so big, so uniform and so flat [6, 7]. Such stretching is predicted by a wide class of theories of particle physics, and all available evidence bears it out. Much of space will continue to stretch forever, but some regions stop stretching and form distinct bubbles. Infinitely many bubbles may emerge, as shown in the lower left of Fig. 7.1, each being an infinite embryonic Level I multiverse filled with matter deposited by the energy field that drove inflation.⁴ Recent cosmological measurements have confirmed two key predictions of inflation: that space has negligible curvature and that the clumpiness in the cosmic matter distribution was approximately scale-invariant.

7.3.2 What are Level II parallel universes like?

The prevailing view is that the physics we observe today is merely a low-energy limit of a much more general theory that manifests itself at extremely high temperatures. For example, this underlying fundamental theory may be 10-dimensional, supersymmetric and involve a grand unification of the four fundamental forces of nature. A common feature in such theories is that the potential energy of the field relevant to inflation has many different minima ('metastable vacuum states'), these corresponding to different effective laws of physics for our low-energy world. For instance, all but three spatial dimensions could be curled up ('compactified') on a tiny scale, resulting in a space like ours, or fewer could curl up, leaving a 5-dimensional space. Quantum fluctuations during inflation can therefore cause different post-inflation bubbles in the Level II multiverse to end up with different effective laws of physics, different dimensionality and different numbers of generations of quarks.

In addition to these discrete properties, our universe is characterized by a set of dimensionless *physical constants*, for example the electron/proton mass ratio, $m_p/m_e \approx 1836$, and the cosmological constant, which appears to be

⁴ Surprisingly, it has been shown that inflation can produce an infinite Level I multiverse even in a bubble of finite volume. This is because the spatial directions of spacetime curve towards the (infinite) time direction [8].

about 10^{-123} in Planck units. There are also models where such non-integer parameters can vary from one post-inflationary bubble to another.⁵ So the Level II multiverse is likely to be more diverse than the Level I multiverse, containing domains where not only the initial conditions differ, but also the physical constants.

This is currently a very active research area. In string theory ‘landscape’ [9,10], the potential has perhaps 10^{500} different minima, so this may offer a specific realization of the Level II multiverse. This would have four sub-levels of increasing diversity.

- **IIId** Different ways in which space can be compactified, allowing both different dimensionality and different symmetries and elementary particles.
- **IIc** Different ‘fluxes’ (generalized magnetic fields) that stabilize the extra dimensions, this being where the largest number of choices enter.
- **IIb** Once these two choices have been made, there may still be a handful of different minima in the effective supergravity potential.
- **IIa** The same minimum and effective laws of physics can be realized in many different post-inflationary bubbles, each constituting a Level I multiverse.

Let us briefly comment on a few closely related multiverse notions. An idea proposed by Tolman [11] and Wheeler [12], and recently elaborated by Steinhardt and Turok [13], is that the Level I multiverse is cyclic, going through an infinite series of big bangs. If it exists, the ensemble of such incarnations would also form a multiverse, arguably with a diversity similar to that of Level II. An idea proposed by Smolin [14] involves an ensemble similar in diversity to that of Level II, but mutating and sprouting new universes through black holes rather than inflation. This predicts a form of natural selection favouring universes with maximal black hole production. In brane-world scenarios, another 3-dimensional world could be literally parallel to ours but offset in a higher dimension. However, it is unclear whether such a world should be regarded as separate from our own, since we may be able to interact with it gravitationally.

⁵ Although the fundamental equations of physics are the same throughout the Level II multiverse, the approximate effective equations governing the low-energy world that we observe will differ. For instance, moving from a 3-dimensional to a 4-dimensional (non-compactified) space changes the observed gravitational force equation from an inverse square law to an inverse cube law. Likewise, breaking the underlying symmetries of particle physics differently will change the line-up of elementary particles and the effective equations that describe them. However, we will reserve the terms ‘different equations’ and ‘different laws of physics’ for the Level IV multiverse, where it is the fundamental rather than effective equations that change.

Note that, if one Level II multiverse can exist, eternally self-reproducing in a fractal pattern, then there may well be infinitely many other ones that are completely disconnected. However, this variant appears to be untestable, since it would neither add any qualitatively different worlds nor alter the probability distribution for their properties. All possible initial conditions and symmetry-breakings are already realized within each one.

7.3.3 *Fine-tuning and selection effects*

Physicists like to explain as much as possible, and some features of our universe seem to be explained by the presence of life. For example, consider the mass of the Sun. The mass of a star determines its luminosity, and using basic physics, one can compute that life as we know it on Earth is possible only if the Sun's mass falls into the narrow range between 1.6×10^{30} kg and 2.4×10^{30} kg. Otherwise Earth's climate would be colder than that of present-day Mars or hotter than that of present-day Venus. The actual mass of the Sun is 2.0×10^{30} kg, which at first glance appears to be a wild stroke of luck. Stellar masses run from 10^{29} kg to 10^{32} kg, so if the Sun's mass were chosen at random, it would have only a small chance of falling into the habitable range. But one can explain this coincidence by postulating an ensemble of planetary systems, together with the selection effect that we must find ourselves living on a habitable planet. Such observer-related selection effects are referred to as 'anthropic' [15]. Although the 'A-word' is notoriously controversial, physicists broadly agree that these selection effects cannot be neglected when testing fundamental theories. In this weak sense, it is obligatory.

What applies to planetary systems also applies to parallel universes. For example, as illustrated in Fig. 7.3, one can consider other universes in which the number of time and space dimensions is different from observed and show that this is inconsistent with life. Most, if not all, of the attributes set by symmetry-breaking appear to be fine-tuned. Changing their values by modest amounts would have resulted in a qualitatively different universe, in which we probably would not exist. If protons were 0.2% heavier, they would decay into neutrons, destabilizing atoms. If the electromagnetic force were 4% weaker, there would be no hydrogen and no normal stars. This is illustrated by Fig. 7.4, which shows constraints on the strong and electromagnetic coupling constants. If the weak interaction were much weaker, hydrogen would not exist; if it were much stronger, supernovae would fail to seed interstellar space with heavy elements. If the cosmological constant were much larger, our universe would have blown itself apart before

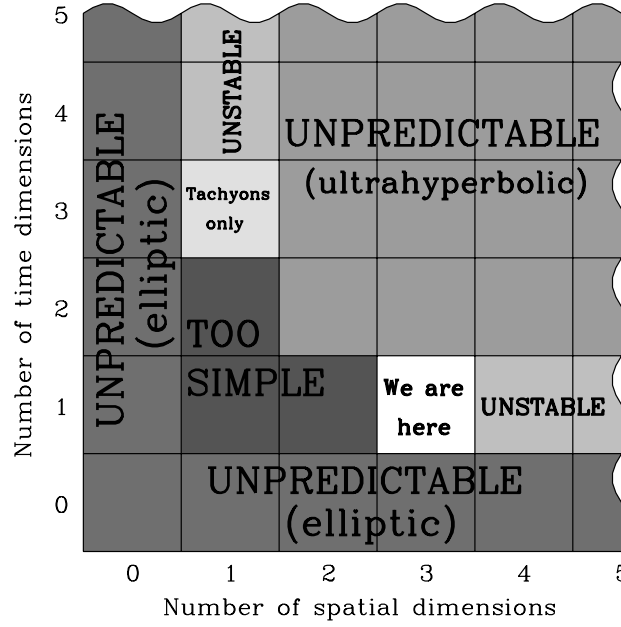


Fig. 7.3. Why we should not be surprised to find ourselves living in 3+1-dimensional spacetime. When the partial differential equations of nature are elliptic or ultrahyperbolic, physics has no predictive power for an observer. In the remaining (hyperbolic) cases, $n > 3$ admits no stable atoms and $n < 3$ may lack sufficient complexity for observers (no gravitational attraction, topological problems). From ref. [16].

galaxies could form. Indeed, most, if not all, of the parameters affecting low-energy physics appear fine-tuned, in the sense that changing them by modest amounts results in a qualitatively different universe.

Although the degree of fine-tuning is still debated [17–19], these examples suggest the existence of parallel universes with other values of some physical constants. If this is the case, physicists will never be able to determine the values of all physical constants from first principles. All they can do is compute probability distributions for what they should expect to find, taking selection effects into account. The result should be as generic as is consistent with our existence.

7.4 Level III: the ‘many worlds’ of quantum physics

If the fundamental equations of physics are *unitary*, as they so far appear to be, then the universe keeps dividing into parallel branches. Whenever a quantum event appears to have a random outcome, all outcomes should occur, one in each branch. This is illustrated by the bottom cartoon

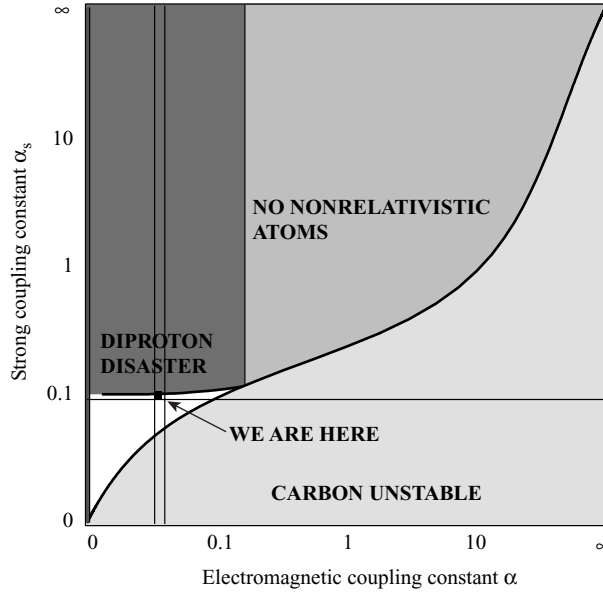


Fig. 7.4. Hints of fine-tuning for the parameters α and α_s , which determine the strengths of the electromagnetic force and the strong nuclear force, respectively. The observed values $(\alpha, \alpha_s) \approx (1/137, 0.1)$ are indicated by a filled square. Grand unified theories rule out everything except the narrow strip between the two vertical lines, and deuterium becomes unstable below the horizontal line. In the narrow shaded region to the very left, electromagnetism is weaker than gravity and therefore irrelevant. From ref. [16].

in Fig. 7.5 and corresponds to the Level III multiverse. Although more controversial than Level I and Level II, we will see that (surprisingly) this level adds no new types of universes.

7.4.1 The quantum conundrum

Despite the obvious successes of quantum theory, a heated debate rages about what it really means. The theory specifies the state of the universe not in classical terms, such as the positions and velocities of its particles, but in terms of a ‘wave-function’. According to the Schrödinger equation, the state evolves over time in a fashion termed ‘unitary’, meaning that it rotates in an abstract, infinite-dimensional Hilbert space. Although quantum mechanics is often described as inherently random and uncertain, the wave-function evolves deterministically.

The difficulty is how to connect this wave-function with what we observe. Many legitimate wave-functions correspond to counter-intuitive situations,

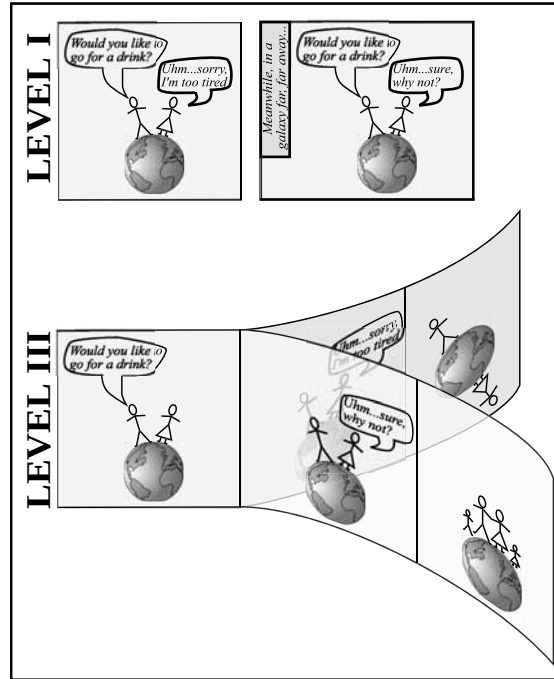


Fig. 7.5. Difference between Level I and Level III. Level I parallel universes are far away in space, whereas those of Level III are right here, with quantum events causing classical reality to split into parallel storylines. Yet Level III adds no new storylines beyond Levels I or II.

such as a cat being dead and alive at the same time in a so-called ‘superposition’. In the 1920s physicists explained away this weirdness by postulating that the wave-function ‘collapses’ into some definite classical state whenever someone makes an observation. This had the virtue of explaining observations, but it turned an elegant (unitary) theory into a messy (non-unitary) one, since there was no equation specifying when or how the collapse occurred. The intrinsic randomness commonly ascribed to quantum mechanics is the result of this postulate, triggering Einstein’s objection that ‘God does not play dice’.

Over the years, many physicists have abandoned this view in favour of one developed in 1957 by Hugh Everett [20]. He showed that the collapse postulate is unnecessary, so that unadulterated quantum theory need not pose any contradictions. Although it predicts that one classical reality gradually splits into superpositions of many such realities, observers subjectively experience this splitting merely as a slight randomness, with probabilities in exact agreement with those predicted by the old collapse postulate [21, 22].

This superposition of classical worlds, which is illustrated in Fig. 7.5, is the Level III multiverse.

7.4.2 What are Level III parallel universes like?

Everett's 'many worlds' interpretation has been puzzling physicists and philosophers for more than four decades. But the theory becomes easier to grasp when one distinguishes between two ways of viewing a physical theory: the outside view of a physicist studying its mathematical equations and the inside view of an observer living in the world described by the equations.⁶

From the outside perspective, the Level III multiverse is simple. There is only one wave-function, which evolves smoothly and deterministically without any splitting. The abstract quantum world described by this evolving wave-function contains a vast number of parallel classical storylines, as well as some quantum phenomena that lack a classical description. From the inside perspective, observers perceive only a tiny fraction of this full reality. They can view their own Level I universe, but a process called decoherence [23,24] – which mimics wave-function collapse while preserving unitarity – prevents them from seeing Level III copies of themselves.

Whenever observers make a decision, quantum effects in their brains lead to a superposition of outcomes, such as 'Continue reading this article' and 'Put down this article'. From the outside perspective, the act of making a decision causes an observer to split into one person who keeps on reading and another one who does not. From their inside perspective, however, each of these *alter egos* is unaware of the other and notices the branching merely as a slight uncertainty in whether or not they continue to read.

Strangely, the same situation occurs in the Level I multiverse. You have evidently decided to keep on reading this article, but one of your *alter egos* in a distant galaxy put it down after the first paragraph. The only difference between Level I and Level III is where your doppelgängers reside.

⁶ The standard picture of the physical world corresponds to an intermediate viewpoint, that could be termed the *consensus view*. From your subjectively perceived internal perspective, the world turns upside down when you stand on your head and disappears when you close your eyes. Yet you subconsciously interpret your sensory inputs as though there is an external reality that is independent of your orientation, your location and your state of mind. Although this third view involves censorship (rejecting dreams), interpolation (between eye-blinks) and extrapolation (attributing existence to unseen cities), independent observers nonetheless appear to share this consensus view. Although the inside view looks black and white to a cat, iridescent to a bird seeing four primary colors, and even more different to a bee seeing polarized light or a bat using sonar, all agree on whether the door is open. The key challenge in physics is to derive this semiclassical consensus view from the fundamental equations specifying the internal perspective. Understanding the nature of human consciousness is an important challenge in its own right, but it may not be necessary for a fundamental theory of physics.

As illustrated in Fig. 7.5, they live elsewhere in 3-dimensional space in Level I, but on another quantum branch in infinite-dimensional Hilbert space in Level III.

7.4.3 Level III parallel universes: evidence and implications

The existence of the Level III multiverse depends on the crucial assumption that the time evolution of the wave-function is unitary. So far, experimenters have encountered no departures from unitarity. Indeed, in the past few decades they have confirmed it for ever larger systems, including carbon-60 ‘buckyball’ molecules and kilometre-long optical fibres. On the theoretical side, the case for unitarity has been bolstered by the discovery of decoherence [25]. Some theorists who work on quantum gravity have questioned unitarity; one concern is that evaporating black holes might destroy information, which would be a non-unitary process. But a recent breakthrough in string theory – known as AdS/CFT correspondence – suggests that even quantum gravity is unitary. If so, black holes do not destroy information but merely transmit it elsewhere.

If physics is unitary, then the standard picture of how quantum fluctuations operated early in the big bang must change. Instead of generating initial conditions at random, these fluctuations generated a quantum superposition of all possible initial conditions, which coexisted simultaneously. Decoherence then caused these initial conditions to behave classically in separate quantum branches. The crucial point is that the distribution of outcomes on different quantum branches in a given Hubble volume (Level III) is identical to the distribution of outcomes in different Hubble volumes within a single quantum branch (Level I). This property of the quantum fluctuations is known in statistical mechanics as ergodicity.

The same reasoning applies to Level II. The process of symmetry-breaking did not produce a unique outcome but rather a superposition of all outcomes, which rapidly went their separate ways. So, if physical constants and spacetime dimensionality can vary among parallel quantum branches at Level III, then they will also vary among parallel universes at Level II. Thus the Level III multiverse adds nothing new beyond Levels I and II, just more indistinguishable copies of the same universes. The debate about Everett’s theory therefore seems to be ending in a grand anticlimax, with the discovery of less controversial multiverses (Levels I and II) that are equally large.

Physicists are only beginning to explore the implications of this. For instance, consider the long-standing question of whether the number of universes exponentially increases over time. The surprising answer is no. From

the outside perspective, there is of course only one quantum universe. From the inside perspective, what matters is the number of universes that are distinguishable at a given instant – that is, the number of noticeably different Hubble volumes. At the quantum level, there are $10^{10^{118}}$ universes with temperatures below 10^8 K, which is vast but finite. The evolution of the wave-function therefore corresponds to a never-ending sliding from one of the $10^{10^{118}}$ states to another. First you are in the universe in which you are reading this sentence. Next you are in the universe in which you are reading another sentence. The observer in the second universe is identical to the one in the first except for an extra instant of memories. All possible states exist at every instant, so the passage of time may be in the eye of the beholder – an idea explored by various authors [26–28]. The multiverse framework may thus prove essential to understanding the nature of time.

7.4.4 *Two world views*

Figure 7.6 illustrates that the debate over how classical mechanics emerges from quantum mechanics is just a small piece of a larger puzzle. Indeed, the debate over the interpretation of quantum mechanics – and the broader issue of parallel universes – is in a sense the tip of an iceberg. For there is a still deeper question that arguably goes as far back as Plato and Aristotle. This concerns the status of mathematics and how it relates to physical reality.

Aristotelian paradigm The internal perspective is physically real, while the external perspective and all its mathematical language is merely a useful approximation.

Platonic paradigm The external perspective (the mathematical structure) is physically real, while the internal perspective and all the human language we use to describe it is merely a useful approximation for describing our subjective perceptions.

What is more basic – the internal or external perspective, human language or mathematical language? Your answer will determine how you feel about parallel universes. Our feeling that the Level III multiverse is ‘weird’ merely reflects the extreme difference between the internal and external perspectives. We may break the symmetry by calling the latter weird, because we were all indoctrinated with the Aristotelian paradigm as children, long before we even heard of mathematics. If this is true, there can never be a ‘Theory of Everything’ (TOE), since one is ultimately just explaining certain verbal statements by other verbal statements. This is known as the infinite regress problem [29].

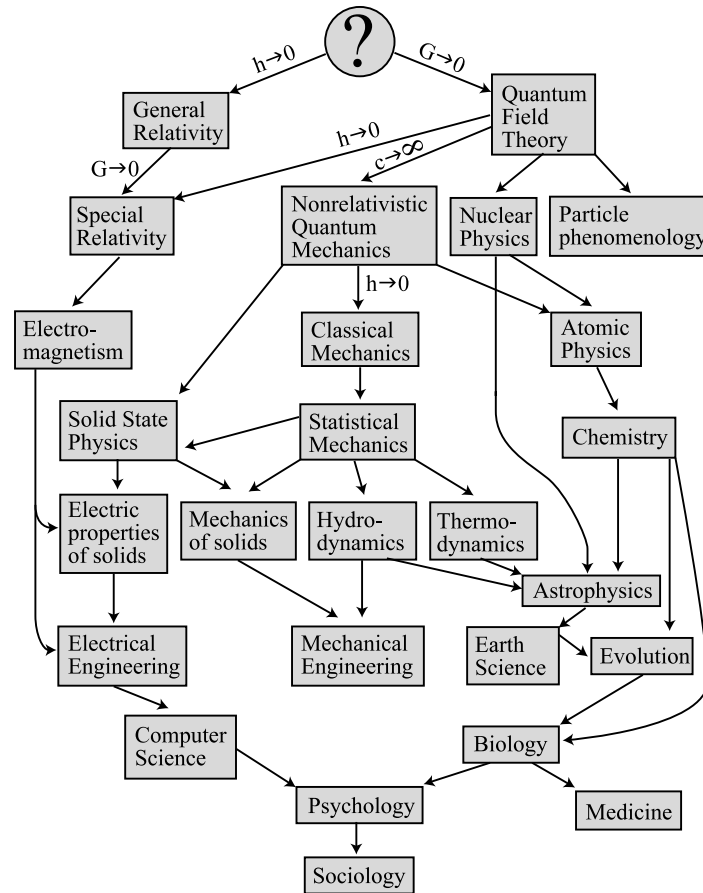


Fig. 7.6. Theories can be crudely organized into a family tree where each might, at least in principle, be derivable from more fundamental ones above it. For example, classical mechanics can be obtained from special relativity in the approximation that the speed of light c is infinite. Most of the arrows are less well understood. All these theories have two components: mathematical equations and words that explain how they are connected to what we observe. At each level in the hierarchy of theories, new words (e.g., protons, atoms, cells, organisms, cultures) are introduced because they are convenient, capturing the essence of what is going on without recourse to the more fundamental theory above it. It is important to remember, however, that it is humans who introduce these concepts and the words for them; in principle, everything could have been derived from the fundamental theory at the top of the tree, although such an extreme reductionist approach would be useless in practice. Crudely speaking, the ratio of equations to words decreases as we move down the tree, dropping to near zero for highly applied fields, such as medicine and sociology. In contrast, theories near the top are highly mathematical, and physicists are still struggling to understand the concepts, if any, in terms which we can understand. The Holy Grail of physics is to find a ‘Theory of Everything’ from which all else can be derived. If such a theory exists at all, it should replace the big question mark at the top of the theory tree. However, something is missing here, since we lack a consistent theory unifying gravity with quantum mechanics.

On the other hand, if you prefer the Platonic paradigm, you should find multiverses natural. In this case, all of physics is ultimately a mathematics problem, since an infinitely intelligent mathematician – given the fundamental equations of the cosmos – could in principle *compute* the internal perspective, i.e. what self-aware observers the universe would contain, what they would perceive, and what language they would invent to describe their perceptions to one another. In other words, there is a TOE at the top of the tree in Fig. 7.6, whose axioms are purely mathematical.

7.5 Level IV: other mathematical structures

If one accepts the Platonist paradigm and believes that there really is a TOE at the top of Fig. 7.6, even though we have not found the correct equations yet, then this question arises: why these particular equations and not others? The Level IV multiverse involves the idea of mathematical democracy, in which universes governed by other equations are equally real. This implies the notion that a mathematical structure and the physical world are in some sense identical. It also means that mathematical structures are ‘out there’, in the sense that mathematicians discover them rather than create them.

7.5.1 What is a mathematical structure?

Many of us think of mathematics as a bag of tricks that we learned in school for manipulating numbers. Yet most mathematicians have a very different view of their field. They study more abstract objects, such as functions, sets, spaces and operators and try to prove theorems about the relations between them. Indeed, some modern mathematics papers are so abstract that the only numbers you will find in them are the page numbers! Despite the plethora of mathematical structures with intimidating names like orbifolds and Killing fields, a striking underlying unity has emerged in the twentieth century: *all* mathematical structures are just special cases of one and the same thing, so-called formal systems. A formal system consists of abstract symbols and rules for manipulating them, specifying how new strings of symbols referred to as theorems can be derived from given ones referred to as axioms. This historical development represented a form of deconstructionism, since it stripped away all meaning and interpretation that had traditionally been given to mathematical structures and distilled out only the abstract relations capturing their very essence. As a result, computers can now prove theorems about geometry without having any physical intuition whatsoever about what space is like.

7.5.2 Is the physical world a mathematical structure?

Although traditionally taken for granted by many theoretical physicists, the notion that the physical world (specifically, the Level III multiverse) is a mathematical structure is deep and far-reaching. It means that mathematical equations describe not merely some limited aspects of the physical world, but *all* aspects of it, leaving no freedom for, say, miracles or free will in the traditional sense. Thus there is some mathematical structure that is *isomorphic* (and hence equivalent) to our physical world, with each physical entity having a unique counterpart in the mathematical structure and vice versa.

Let us consider some examples. A century ago, when classical physics still reigned supreme, many scientists believed that physical space was isomorphic to the three-dimensional Euclidean space $\mathbb{R}^3$. Moreover, some thought that all forms of matter in our universe corresponded to various classical *fields*: the electric field, the magnetic field and perhaps a few undiscovered ones, mathematically corresponding to functions on $\mathbb{R}^3$. In this view (later proven incorrect), dense clumps of matter such as atoms were simply regions in space where some fields were strong. These fields evolved deterministically according to some partial differential equations, and observers perceived this as things moving around and events taking place. However, fields in 3-dimensional space cannot be the mathematical structure corresponding to our universe, because a mathematical structure is an abstract, immutable entity existing outside of space and time. Our familiar perspective of a 3-dimensional space, where events unfold, is equivalent to a 4-dimensional spacetime, so the mathematical structure must be fields in 4-dimensional space. In other words, if history were a movie, the mathematical structure would not correspond to a single frame of it, but to the entire videotape.

Given a mathematical structure, we will say that it has *physical existence* if any self-aware substructure (SAS) within it subjectively perceives itself as living in a physically real world. In the above classical physics example, an SAS would be a tube through spacetime, a thick version of its world-line. Within the tube, the fields would exhibit certain complex behaviour, corresponding to storing and processing information about the field-values in the surroundings, and at each position along the tube these processes would give rise to the familiar but mysterious sensation of self-awareness. The SAS would perceive this 1-dimensional string of perceptions along the tube as passage of time.

Although this example illustrates how our physical world can *be* a mathematical structure, this particular structure (fields in four-dimensional space)

is now known to be the wrong one. After realizing that spacetime could be curved, Einstein searched for a unified field theory where the universe was a four-dimensional pseudo-Riemannian manifold with tensor fields. However, this failed to account for the observed behaviour of atoms. According to quantum field theory, the modern synthesis of special relativity theory and quantum theory, our universe (in this case the Level III multiverse) is a mathematical structure with an algebra of operator-valued fields. Here the question of what constitutes an SAS is more subtle [30]. However, this fails to describe black hole evaporation, the first instance of the big bang and other quantum gravity phenomena. So the true mathematical structure isomorphic to our universe, if it exists, has not yet been found.

7.5.3 *Mathematical democracy*

Suppose that our physical world really is a mathematical structure and that you are an SAS within it. This means that this particular structure enjoys physical as well as mathematical existence. What about all the other possible mathematical structures? Do they too enjoy physical existence? If not, there would be a fundamental, unexplained ontological asymmetry built into the very heart of reality, splitting mathematical structures into two classes: those with and without physical existence. As a way out of this philosophical conundrum, I have suggested [18] that complete mathematical democracy holds – that mathematical existence and physical existence are equivalent, so that *all* mathematical structures exist physically as well. This is the Level IV multiverse. It can be viewed as a form of radical Platonism, asserting that the mathematical structures in Plato’s *realm of ideas* and Rucker’s *mindscapes* [31] exist ‘out there’ in a physical sense [32]. This casts the so-called modal realism theory of David Lewis [33] in mathematical terms, akin to what Barrow [34, 35] refers to as ‘pi in the sky’. If this theory is correct, then – since it has no free parameters – all properties of all parallel universes (including the subjective perceptions of every SAS) could in principle be derived by an infinitely intelligent mathematician.

7.5.4 *Evidence for a Level IV multiverse*

Why should we believe in Level IV? Logically, it rests on the two following separate assumptions.

Assumption 1 The physical world (specifically our Level III multiverse) is a mathematical structure.

Assumption 2 All mathematical structures exist ‘out there’ in the same sense (mathematical democracy).

In a famous essay, Wigner [36] argued that ‘the enormous usefulness of mathematics in the natural sciences is something bordering on the mysterious’ and that ‘there is no rational explanation for it’. This argument can be taken as support for Assumption 1; here the utility of mathematics for describing the physical world is a natural consequence of the fact that the latter *is* a mathematical structure, which we are uncovering bit by bit. The various approximations that constitute our current physics theories are successful because mathematical structures can provide good approximations to how an SAS will perceive more complex mathematical structures. In other words, our successful theories are not mathematics approximating physics but mathematics approximating mathematics. Wigner’s observation is unlikely to be based on fluke coincidences, since far more mathematical regularity has been discovered in nature in the decades since he made it.

A second argument supporting Assumption 1 is that abstract mathematics is so general that *any* TOE that is definable in purely formal terms is also a mathematical structure. For instance, a TOE involving a set of different types of entities (words, say) and relations between them (additional words) is a set-theoretical model, and one can generally find a formal system of which it is a model. This argument also makes Assumption 2 more appealing, since it implies that *any* conceivable parallel universe theory can be described at Level IV. The Level IV multiverse, termed the ‘ultimate ensemble theory’ in ref. [16] since it subsumes all other ensembles, therefore brings closure to the hierarchy of multiverses, and there cannot be a Level V. Considering an ensemble of mathematical structures does not add anything new, since this is still just another mathematical structure.

What about the notion that our universe is a computer simulation? This idea occurs frequently in science fiction and has been substantially elaborated [37,38]. The information content (memory state) of a digital computer is a long string of bits, equivalent to some large but finite integer n written in binary form (e.g. 1001011100111001...). The information-processing of a computer is a deterministic rule for repeatedly changing each memory state into another one. Mathematically, it is a function f mapping the integers onto themselves that is iterated: $n \mapsto f(n) \mapsto f(f(n)) \mapsto \dots$. In other words, even the most sophisticated computer simulation is just another special case of a mathematical structure, and this is already included in the Level IV multiverse.

A second argument for Assumption 2 is that if two entities are isomorphic, then there is no meaningful sense in which they are not the same [39]. This applies when the entities in question are a physical universe and the mathematical structure describing it. To avoid the conclusion that mathematical

and physical existence are equivalent, one would need to argue that our universe is somehow made of stuff perfectly described by a mathematical structure, but which also has other properties that are not described by it. However, this violates Assumption 1 and implies that either it is isomorphic to a more complicated mathematical structure or it is not mathematical at all.

Having universes dance to the tune of all possible equations also resolves the fine-tuning problem, even at the fundamental equation level. Although many (if not most) mathematical structures are likely to be devoid of an SAS, failing to provide the complexity, stability and predictability that it requires, we know we must inhabit a mathematical structure capable of supporting life. Because of this selection effect, the answer to the question ‘what is it that breathes fire into the equations and makes a universe for them to describe?’ [40] would then be ‘you, the SAS’.

7.5.5 What are Level IV parallel universes like?

We can test and potentially rule out any theory by computing probability distributions for our future perceptions – given our past perceptions – and comparing the predictions with the observed outcome. In a multiverse theory, there is typically more than one SAS that has experienced a past life identical to yours, so there is no way to determine which one is you. To make predictions, you therefore have to compute what fractions of them will perceive what in the future. This leads to the following possibilities.

Prediction 1 The mathematical structure describing our world is the most generic one that is consistent with our observations.

Prediction 2 Our future observations are the most generic ones that are consistent with our past observations.

Prediction 3 Our past observations are the most generic ones that are consistent with our existence.

We will return to the problem of what ‘generic’ means (i.e. the measure problem) later. However, one striking feature of mathematical structures, discussed in detail in ref. [16], is that the sort of symmetry and invariance properties that are responsible for the simplicity and orderliness of our universe tend to be more the rule than the exception – mathematical structures have them by default and complicated additional axioms must be added to make them go away. Because of this, as well as selection effects, we should not necessarily expect life in the Level IV multiverse to be disordered.

7.6 Discussion

We have seen that scientific theories of parallel universes form a four-level hierarchy, in which universes become progressively more different from our own. They might have different initial conditions (Level I), different effective physical laws, constants and particles (Level II), or different fundamental physical laws (Level IV). It is ironic that Level III is the one that has drawn most criticism, because it is the only one that adds no qualitatively new types of universe. Whereas the Level I universes join seamlessly, there are clear demarcations between those within Level II (caused by inflation) and Level III (caused by decoherence). The Level IV universes are completely disconnected and need to be considered together only for predicting your future, since ‘you’ may exist in more than one of them.

7.6.1 *Future prospects*

There are ample future prospects for testing and perhaps ruling out these multiverse theories. In the coming decade, dramatically improved cosmological measurements of the microwave background radiation and the large-scale matter distribution will test both Level I (by further constraining the curvature and topology of space) and Level II (by providing stringent tests of inflation). Progress in both astrophysics and high-energy physics should also clarify the extent to which various physical constants are fine-tuned, thereby weakening or strengthening the case for Level II. If the current effort to build quantum computers succeeds, it will provide further evidence for Level III, since they would essentially exploit the parallelism of the Level III multiverse for parallel computation [27]. Conversely, experimental evidence of unitarity violation would rule out Level III. Finally, success or failure in the grand challenge of modern physics, unifying general relativity and quantum field theory, will shed more light on Level IV. Either we will eventually find a mathematical structure which matches our universe, or the unreasonable effectiveness of mathematics will be found to be limited and we will have to abandon Level IV.

7.6.2 *The measure problem*

There are also interesting theoretical issues to resolve within the multiverse theories, in particular the *measure problem*. As multiverse theories gain credence, the sticky issue of how to compute probabilities in physics is growing from a minor nuisance into a major embarrassment. If there are indeed many identical copies of you, the traditional notion of determinism

evaporates. You could not compute your own future even if you had complete knowledge of the entire state of the multiverse, because there is no way for you to determine which of these copies is you. All you can predict are probabilities for what you would observe. If an outcome has a probability of 50%, this means that half the observers observe that outcome.

Unfortunately, it is not an easy task to compute what fraction of the infinitely many observers perceive what. The answer depends on the order in which you count them. By analogy, the fraction of the integers that are even is 50% if you order them numerically (1, 2, 3, 4, ...), but approaches 100% if you sort them digit by digit, the way your word processor would (1, 10, 100, 1000, ...). When observers reside in disconnected universes, there is no obviously natural way in which to order them. Instead one must sample from the different universes with some statistical weights referred to as a ‘measure’.

This problem crops up in a mild manner at Level I, becomes severe at Level II [41], has caused much debate at Level III [21, 22, 42] and is horrendous at Level IV. At Level II, for instance, several people have published predictions for the probability distributions of various cosmological parameters. They have argued that the different universes that have inflated by different amounts should be given statistical weights proportional to their volume [2]. On the other hand, $2 \times \infty = \infty$, so there is no objective sense in which an infinite universe that has expanded by a factor of two has become larger. Moreover, a finite universe with the topology of a torus is equivalent to a periodic universe with infinite volume, both mathematically and from the perspective of an observer within it. So why should its infinitely smaller volume give it zero statistical weight? After all, even in the Level I multiverse, Hubble volumes start repeating (albeit randomly rather than periodically) after about $10^{10^{18}}$ m. The problem of assigning statistical weights to different mathematical structures at Level IV is even more difficult. The fact that our universe seems relatively simple has led many people to suggest that the correct measure must somehow involve complexity.

7.6.3 *The pros and cons of parallel universes*

So should you believe in parallel universes? The principal arguments against them are that they are wasteful and that they are weird. The wastefulness argument is that multiverse theories are vulnerable to Occam’s razor because they postulate the existence of other worlds that we can never observe. Yet this argument can be turned around. For what precisely would nature be

wasting? Certainly not space, mass or atoms – the uncontroversial Level I multiverse already contains an infinite amount of all three.

The real issue here is the apparent reduction in simplicity. One might worry about all the information necessary to specify all those unseen worlds. But an entire ensemble is often much simpler than one of its members. This principle can be stated more formally using the notion of algorithmic information content. The algorithmic information content in a number is, roughly speaking, the length of the shortest computer program that will produce that number as output. For example, consider the set of all integers. Naïvely, you might think that a single number is simpler than the whole set of numbers, but the set can be generated by a trivial computer program, whereas a single number can be hugely long. Therefore, the whole set is actually simpler. Similarly, the set of all solutions to Einstein’s field equations is simpler than a specific solution. The former is described by a few equations, whereas the latter requires the specification of vast amounts of initial data on some hypersurface.

The lesson is that complexity increases when we restrict our attention to one particular element in an ensemble, thereby losing the symmetry and simplicity that were inherent in the totality of all the elements taken together. In this sense, the higher-level multiverses are simpler. Going from our universe to the Level I multiverse eliminates the need to specify initial conditions, upgrading to Level II eliminates the need to specify physical constants, and the Level IV multiverse eliminates the need to specify anything at all. The opulence of complexity is all in the subjective perceptions of observers [43].

The weirdness objection is aesthetic rather than scientific and only makes sense in the Aristotelian worldview. Yet when we ask a profound question about the nature of reality, we surely expect an answer that sounds strange. Evolution provided us with intuition for the everyday physics that had survival value for our distant ancestors, so whenever we venture beyond the everyday world, we should expect it to seem bizarre. Thanks to clever inventions, we have glimpsed slightly beyond our normal subjective view and thereby encountered bizarre phenomena (e.g. at high speeds, small and large scales, low and high temperatures).

A common feature of all four multiverse levels is that the simplest and arguably most elegant theory involves parallel universes by default. To deny the existence of those universes, one needs to complicate the theory by adding experimentally unsupported processes and *ad hoc* postulates: finite space, wave-function collapse, ontological asymmetry, etc. Our judgement therefore comes down to which we find more wasteful and inelegant: many worlds

or many words. Perhaps we will gradually become more used to the weird ways of our cosmos, and even find its strangeness to be part of its charm.

Acknowledgements

The author wishes to thank Anthony Aguirre, Aaron Classens, Marius Cohen, Angelica de Oliveira-Costa, Alan Guth, Shamit Kachru, Andrei Linde, George Musser, David Raub, Martin Rees, Harold Shapiro, Alex Vilenkin and Frank Wilczek for stimulating discussions. This work was supported by NSF grants AST-0071213 and AST-0134999, NASA grants NAG5-9194 and NAG5-11099, a fellowship from the David and Lucile Packard Foundation and a Cottrell Scholarship from Research Corporation.

References

- [1] G. B. Brundrit. Life in the infinite universe. *Quart. J. Roy. Astron. Soc.* **20** (1979), 37.
- [2] J. Garriga and A. Vilenkin. A prescription for probabilities in eternal inflation. *Phys. Rev. D* **64** (2001), 023507.
- [3] G. F. R. Ellis. *Are We Alone?* (New York: Perseus, 1995).
- [4] A. de Oliveira-Costa, M. Tegmark, M. Zadamiaga and A. Hamilton. Significance of the largest scale CMB fluctuations in WMAP. *Phys. Rev. D* **69** (2004), 063516.
- [5] N. J. Cornish, D. N. Spergel, G. D. Starkman and E. Komatsu. Constraining the topology of the universe. *Phys. Rev. Lett.* **92** (2004), 201302.
- [6] A. Linde. The self-reproducing inflationary universe. *Sci. Am.* **271** (1994), 32.
- [7] A. H. Guth and D. I. Kaiser. Inflationary cosmology: Exploring the universe from the smallest to the largest scales. *Science*, **307** (2005), 884.
- [8] M. A. Bucher and D. N. Spergel. Inflation in a low-density universe. *Sci. Am.* **280** (1999), 62.
- [9] R. Bousso and J. Polchinski. Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. *JHEP* **0006** (2000), 006.
- [10] L. Susskind. This volume (2007) [hep-th/0302219].
- [11] R. C. Tolman. *Relativity, Thermodynamics, and Cosmology* (Oxford: Clarendon Press, 1934).
- [12] J. A. Wheeler. Beyond the end of time. In *Black Holes, Gravitational Waves and Cosmology: An Introduction to Current Research*, eds. M. Rees, R. Ruffini and J. A. Wheeler (New York: Gordon and Breach, 1974).
- [13] P. J. Steinhardt and N. Turok. A cyclic model of the universe. *Science*, **296** (2002), 1436.
- [14] L. Smolin. *The Life of the Cosmos* (Oxford: Oxford University Press, 1997).
- [15] B. Carter. Number coincidences and the anthropic principle in cosmology. In *Confrontation of Cosmological Theory with Observational Data*, ed. M. S. Longair (Dordrecht: Reidel, 1974), p. 291.
- [16] M. Tegmark. On the dimensionality of spacetime. *Class. Quant. Grav.* **14** (1997), L69.

- [17] J. D. Barrow and F. J. Tipler. *The Anthropic Cosmological Principle* (Oxford: Clarendon, 1986).
- [18] M. Tegmark. Is ‘the theory of everything’ merely the ultimate ensemble theory? *Ann. Phys.* **270** (1998), 1.
- [19] C. J. Hogan. Why the Universe is Just So. *Rev. Mod. Phys.* **72** (2000), 1149.
- [20] H. Everett. Relative state formulations of quantum theory. *Rev. Mod. Phys.* **29** (1957), 454.
- [21] H. Everett. In *The Many-Worlds Interpretation of Quantum Mechanics*, eds. B. S. DeWitt and N. Graham (Princeton, NJ: Princeton University Press, 1973).
- [22] B. de Witt. The Everett interpretation of quantum mechanics. In *Science and Ultimate Reality: From Quantum to Cosmos*, eds. J. D. Barrow, P. C. W. Davies and C. L. Harper (Cambridge: Cambridge University Press, 2003), pp. 167–98.
- [23] H. D. Zeh. On the interpretation of measurement in quantum theory. *Found. Phys.* **1** (1970), 69.
- [24] D. Giulini, E. Joos, C. Kiefer, J. Kupsch, I. O. Stamatescu and H. D. Zeh. *Decoherence and the Appearance of a Classical World in Quantum Theory* (Berlin: Springer, 1996).
- [25] M. Tegmark and J. A. Wheeler. 100 years of quantum mysteries. *Sci. Am.* **284** (2001), 68.
- [26] G. Egan. *Permutation City* (New York: Harper, 1995).
- [27] D. Deutsch. *The Fabric of Reality* (New York: Allen Lane, 1997).
- [28] J. B. Barbour. *The End of Time* (Oxford: Oxford University Press, 2001).
- [29] R. Nozick. *Philosophical Explanations* (Cambridge, MA: Harvard University Press, 1981).
- [30] M. Tegmark. The importance of quantum decoherence in brain processes. *Phys. Rev. E* **61** (2000), 4194.
- [31] R. Rucker. *Infinity and the Mind* (Boston: Birkhauser, 1982).
- [32] P. C. W. Davies. *The Mind of God* (New York: Simon and Schuster, 1992).
- [33] D. Lewis. *On the Plurality of Worlds* (Oxford: Blackwell, 1986).
- [34] J. D. Barrow. *Theories of Everything* (New York: Ballantine, 1991).
- [35] J. D. Barrow. *Pi in the Sky* (Oxford: Clarendon, 1992).
- [36] E. P. Wigner. *Symmetries and Reflections* (Cambridge, MA: MIT Press, 1967).
- [37] J. Schmidhuber. A computer scientist’s view of life, the universe, and everything. In *Foundations of Computer Science: Potential Theory Cognition*, ed. C. Freksa. Lecture Notes in Computer Science (Berlin: Springer, 1997).
- [38] S. Wolfram. *A New Kind of Science* (New York: Wolfram Media, 2002).
- [39] M. Cohen. Master’s thesis, Department of Philosophy, Ben Gurion University of the Negev (2003).
- [40] S. Hawking. *A Brief History of Time* (New York: Touchstone, 1993).
- [41] M. Tegmark. What does inflation really predict? *J. Cosmol. Astropart. Phys.* **0504** (2004), 001.
- [42] V. F. Mukhanov. This volume (2007).
- [43] M. Tegmark. Does the universe in fact contain almost no information? *Found. Phys. Lett.* **9** (1996), 25.

8

The inflationary multiverse

Andrei Linde

Department of Physics, Stanford University

8.1 Introduction

At the beginning of the 1980s, when the inflationary theory was first proposed, one of our main goals was to explain the amazing uniformity of the Universe. We were trying to find out why the Universe looks approximately the same in all directions. Of course, locally the Universe does not look uniform – there are such large deviations from uniformity as planets, stars and galaxies. But if one considers the density of matter on scales comparable to the size of the observable Universe, $l_{\text{obs}} \sim 10^{28}$ cm, one finds that this is uniform to an accuracy better than one part in 10 000. The most surprising thing about this is that, according to the standard big bang theory, the distant parts of the Universe which we can see with a powerful telescope were not in causal contact at the time of the big bang and could not have been in such contact until very late stages of cosmic evolution. So one could only wonder what made these distant parts of the Universe so similar to each other.

In the absence of any reasonable explanation, cosmologists invented the so-called ‘cosmological principle’, which claims that the Universe *must* be uniform. But the Universe is not perfectly uniform, since it contains inhomogeneities – such as stars and galaxies – which are crucial for life. Because of these small but important violations, the cosmological principle cannot be a true principle of nature, just like a person who takes only small bribes cannot be called a man of principle.

Even though the cosmological principle could not explain the observed properties of the Universe, it was taken for granted by almost all scientists. We believed that the Universe looks the same everywhere and that the physical laws in all of its parts are identical to those in the vicinity of the solar system. We were looking for a unique and beautiful theory that would

unambiguously predict the observed values for all parameters of all elementary particles, not leaving any room for pure chance.

However, most of the parameters describing elementary particles look more like a collection of random numbers than a unique manifestation of some hidden harmony of nature. Also it was pointed out long ago that a minor change (by a factor of two or three) in the mass of the electron, the fine-structure constant, the strong-interaction constant or the gravitational constant would lead to a world in which life as we know it could never have arisen. Adding or subtracting even a single spatial dimension of the same type as the usual three dimensions would make planetary systems impossible. Indeed, in spacetimes with dimensionality $d > 4$, the gravitational force between bodies falls off faster than r^{-2} , while in spacetimes with $d < 4$, general relativity tell us that such forces are absent altogether. This rules out the existence of stable planetary systems for $d \neq 4$. Furthermore, in order for life as we know it to exist, it is necessary that the Universe be sufficiently large, flat, homogeneous and isotropic. These facts, as well as a number of other observations, lie at the foundation of the so-called anthropic principle [1–3]. According to this principle, we observe the Universe to be as it is because only in one like ours could observers exist.

Many scientists are still ashamed of using the anthropic principle. Just as the friends of Harry Potter were afraid of saying the name ‘Voldemort’, the opponents of the anthropic principle often say that they do not want to use the ‘A’ word in their research. This critical attitude is quite understandable. Historically, the anthropic principle was often associated with the idea that the Universe was created many times until the final success. It was not clear who did it and why it was necessary to make the Universe suitable for our existence. Moreover, it would be much simpler to create proper conditions for our existence in a small vicinity of the solar system rather than in the whole Universe. Why would one need to work so hard?

Fortunately, most of the problems associated with the anthropic principle were resolved [4–7] soon after the invention of inflationary cosmology [8–12]. Inflationary theory was able to explain the homogeneity of our part of the Universe, while simultaneously predicting that on a very large scale, much greater than $l_{\text{obs}} \sim 10^{28}$ cm, the Universe can be completely inhomogeneous, looking not like a sphere but like a huge growing fractal. The different parts of this fractal are enormous and may have dramatically different properties. They are connected to each other, but the distance between them is so large that for all practical purposes they look like separate universes.

Thus, although inflationary theory was able to explain the local homogeneity of the Universe, many of its versions predicted that on super-large

scales one has a ‘multiverse’, consisting of many universes with different properties. In the context of this scenario, we were able for the first time to make sense of the basic premise of the anthropic principle: there is not just one copy of the Universe – we actually have a choice!

8.2 Chaotic inflation

In order to explain this picture in more detail, I will first describe the basic features of inflation. I will concentrate on the simplest version – the chaotic inflation scenario [11]. To explain the main idea of chaotic inflation, let us consider the simplest model of a scalar field ϕ , with a mass m and potential energy density $V(\phi) = \frac{1}{2}m^2\phi^2$, as shown in Fig. 8.1. Since this function has a minimum at $\phi = 0$, one may expect the scalar field to oscillate near this minimum. This is indeed the case if the Universe does not expand. However, one can show that – in a rapidly expanding universe – the scalar field moves

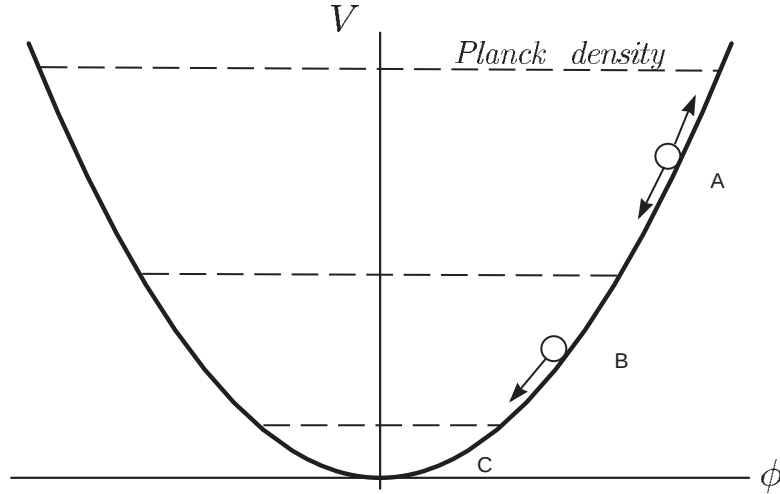


Fig. 8.1. Motion of the scalar field in the theory with $V(\phi) = \frac{1}{2}m^2\phi^2$. If the potential energy density of the field is greater than the Planck density, $\rho_p \sim M_p^4 \sim 10^{94} \text{ g cm}^{-3}$, quantum fluctuations of spacetime are so strong that one cannot describe it in the usual terms. Such a state is called spacetime foam. At a somewhat smaller energy density (region A: $mM_p^3 < V(\phi) < M_p^4$) quantum fluctuations of spacetime are small but quantum fluctuations of the scalar field ϕ may be large. Jumps of the scalar field due to quantum fluctuations lead to eternal self-reproduction of the inflationary universe. At even smaller values of $V(\phi)$ (region B: $m^2M_p^2 < V(\phi) < mM_p^3$) fluctuations of the field ϕ are small; it moves down slowly like a ball in a viscous liquid. Inflation occurs in both regions A and B. Finally, near the minimum of $V(\phi)$ (region C) the scalar field rapidly oscillates, creates pairs of elementary particles, and the Universe becomes hot.

down very slowly, like a ball in a viscous liquid, with the viscosity being proportional to the speed of expansion.

There are two equations which describe evolution of a homogeneous scalar field in our model: the field equation,

$$\ddot{\phi} + 3H\dot{\phi} = -m^2\phi, \quad (8.1)$$

and the Einstein equation,

$$H^2 + \frac{k}{a^2} = \frac{8\pi}{3M_p^2} \left(\frac{1}{2}\dot{\phi}^2 + V(\phi) \right). \quad (8.2)$$

Here a dot denotes d/dt , $M_p = G^{-1/2}$ is the Planck mass (using units with $\hbar = c = 1$), $a(t)$ is the cosmic scale factor, $H = \dot{a}/a$ is the Hubble parameter and $k = -1, 0, 1$ for an open, flat or closed universe, respectively. The first equation is similar to the equation of motion for a harmonic oscillator, where instead of $x(t)$ we have $\phi(t)$, so the term $3H\dot{\phi}$ is like a friction effect.

If the scalar field ϕ is initially large, the Hubble parameter H is also large from Eq. (8.1). This means that the friction term is large, so the scalar field is moving very slowly. At this stage, the energy density of the scalar field remains almost constant and the expansion of the Universe continues much faster than in the old cosmological theory. Due to the rapid growth of the scale of the Universe and slow motion of the field, soon after the beginning of this regime one has $\ddot{\phi} \ll 3H\dot{\phi}$, $H^2 \gg k/a^2$ and $\dot{\phi}^2 \ll m^2\phi^2$, so the system of equations can be simplified to

$$3\frac{\dot{a}}{a}\dot{\phi} = -m^2\phi, \quad H = \frac{\dot{a}}{a} = \frac{2m\phi}{M_p} \sqrt{\frac{\pi}{3}}. \quad (8.3)$$

The second equation shows that the scale factor in this regime grows approximately as

$$a \sim e^{Ht}, \quad H = \frac{2m\phi}{M_p} \sqrt{\frac{\pi}{3}}. \quad (8.4)$$

This stage of exponentially rapid expansion of the universe is called inflation.

When the field ϕ becomes sufficiently small, H and the viscosity become small, inflation ends and the scalar field begins to oscillate near the minimum of $V(\phi)$. As any rapidly oscillating classical field, it loses its energy by creating pairs of elementary particles. These particles interact with each other and come to a state of thermal equilibrium with some temperature T . From this time on, the Universe can be described by the standard hot big bang theory.

The main difference between inflationary theory and the old cosmology becomes clear when one calculates the size of a typical domain at the end of inflation. Even if the initial size of the inflationary Universe was as small as the Planck scale, $l_p \sim 10^{-33}$ cm, one can show that after 10^{-30} s of inflation this acquires a huge size of $l \sim 10^{10^{12}}$ cm. This makes the Universe almost exactly flat and homogeneous on the large scale, because all inhomogeneities were stretched by a factor of $10^{10^{12}}$. This number is model-dependent, but in all realistic models the size of the Universe after inflation appears to be many orders of magnitude greater than the size of the part of the Universe which we can see now, $l_{\text{obs}} \sim 10^{28}$ cm. This solves most of the problems of the old cosmological theory [13].

If the Universe initially consisted of many domains, with a chaotically distributed scalar field ϕ , then the domains where the scalar field was too small never inflated, so they remain small. The main contribution to the total volume of the Universe will be given by the domains which originally contained a large scalar field. Inflation of such domains creates huge homogeneous islands out of the initial chaos, each one being much greater than the size of the observable part of the Universe. That is why I call this scenario ‘chaotic inflation’.

In addition to the scalar field driving inflation, realistic models of elementary particles involve many other scalar fields ϕ_i . The final values acquired by these fields after the cosmological evolution are determined by the position of the minima of their potential energy density $V(\phi_i)$. In the simplest models, the potential $V(\phi_i)$ has only one minimum. However, in general, $V(\phi_i)$ may have many different minima. For example, in the simplest supersymmetric theory unifying weak, strong and electromagnetic interactions, the effective potential has dozens of different minima of equal depth with respect to the two scalar fields, Φ and φ . If the scalar fields fall to different minima in different parts of the Universe (a process called spontaneous symmetry-breaking), the masses of elementary particles and the laws describing their interactions will be different in these parts. Each of the parts becomes exponentially large because of inflation. In some of them, there will be no difference between weak, strong and electromagnetic interactions, and life of our type will be impossible. Other parts will be similar to the one where we live [14].

This means that, even if we are able to find the final theory of everything, we will be unable to determine uniquely properties of elementary particles; the Universe may consist of different exponentially large domains where the properties of elementary particles are different. This is an important step towards the justification of the anthropic principle. A further step can be made if one takes into account quantum fluctuations produced during inflation.

8.3 Inflationary quantum fluctuations

According to quantum field theory, empty space is not entirely empty. It is filled with quantum fluctuations of all types of physical fields. The wavelengths of all quantum fluctuations of the scalar field ϕ grow exponentially during inflation. When the wavelength of any particular fluctuation becomes greater than H^{-1} , the fluctuation stops oscillating and its amplitude freezes at some non-zero value $\delta\phi(x)$ because of the large friction term $3H\dot{\phi}$ in the equation of motion of the field. The amplitude of this fluctuation then remains almost unchanged for a very long time, whereas its wavelength grows exponentially. Therefore, the appearance of such a frozen fluctuation is equivalent to the appearance of a classical field $\delta\phi(x)$ produced from quantum fluctuations.

Because the vacuum contains fluctuations of all wavelengths, inflation leads to the continuous creation of new perturbations of the classical field with wavelengths greater than H^{-1} . The average amplitude of perturbations generated during a time interval H^{-1} (in which the Universe expands by a factor e) is given by $|\delta\phi(x)| \approx H/(2\pi)$ [15, 16]. These quantum fluctuations are responsible for galaxy formation [17–21]. But if the Hubble constant during inflation is sufficiently large, quantum fluctuations of the scalar fields may lead not only to the formation of galaxies, but also to the division of the Universe into exponentially large domains with different properties.

As an example, consider again the simplest supersymmetric theory unifying weak, strong and electromagnetic interactions. Different minima of the effective potential in this model are separated from each other by a distance $\sim 10^{-3}M_p$. The amplitude of quantum fluctuations in the fields ϕ , Φ and φ at the beginning of chaotic inflation can be as large as $10^{-1}M_p$. This means that, at the early stages of inflation, the fields Φ and φ could easily jump from one minimum of the potential to another. Therefore, even if these fields initially occupied the same minimum everywhere, after the stage of chaotic inflation the Universe becomes divided into many exponentially large domains, corresponding to all possible minima of the effective potential [6, 14].

8.4 Eternal chaotic inflation and string theory landscape

The process of the division of the Universe into different parts becomes even easier if one takes into account the process of self-reproduction of inflationary domains. The basic mechanism can be understood as follows. If quantum fluctuations are sufficiently large, they may locally increase the value of the potential energy of the scalar field in some parts of the Universe. The

probability of quantum jumps leading to a local increase of the energy density can be very small, but the regions where it happens start expanding much faster than their parent domains, and quantum fluctuations inside them lead to the production of new inflationary domains which expand even faster.

Self-reproduction of inflationary domains was first established in the context of the new inflation scenario, which is based on inflation near a local maximum of the potential [4, 22, 23]. The existence of this regime was used for justification of the anthropic principle in ref. [4]. However, nobody paid any attention to this possibility until the discovery of self-reproduction of the Universe in the chaotic inflation scenario [7].

In order to understand this effect, let us consider an inflationary domain of initial radius H^{-1} containing a sufficiently homogeneous field with initial value $\phi \gg M_p$. Equations (8.3) tell us that, during a typical time interval $\Delta t = H^{-1}$, the field inside this domain will be reduced by $\Delta\phi = M_p^2/(4\pi\phi)$. Comparing this expression with the amplitude of quantum fluctuations,

$$\delta\phi \sim \frac{H}{2\pi} = \frac{m\phi}{\sqrt{3\pi}M_p}, \quad (8.5)$$

one can easily see that for $\phi \gg \phi^* \sim M_p \sqrt{M_p/m}$, one has $|\delta\phi| \gg |\Delta\phi|$, i.e. the motion of the field ϕ due to its quantum fluctuations is much more rapid than its classical motion.

During the typical time H^{-1} , the size of the domain of initial size H^{-1} containing the field $\phi \gg \phi^*$ grows e times, its volume increases $e^3 \sim 20$ times, and in almost half of this new volume the field ϕ jumps up instead of down. Thus the total volume of inflationary domains with $\phi \gg \phi^*$ grows approximately ten times. During the next time interval H^{-1} , this process continues, so the Universe enters an eternal process of self-reproduction. I call this process ‘eternal inflation’.

In this scenario, the scalar field may wander for an indefinitely long time as the density approaches the Planck density. This induces quantum fluctuations of all other scalar fields, which may jump from one minimum of the potential to another for an unlimited time. The amplitude of these quantum fluctuations can be extremely large, $\delta\varphi \sim \delta\Phi \sim 10^{-1}M_p$. As a result, quantum fluctuations generated during eternal chaotic inflation can penetrate through any barriers, even if they have Planckian height, and the Universe after inflation becomes divided into an indefinitely large number of exponentially large domains. These contain matter in all possible states, corresponding to all possible mechanisms of spontaneous symmetry-breaking, i.e. to all possible laws of low-energy physics [7, 24].

A rich spectrum of possibilities may appear during inflation in Kaluza–Klein and superstring theories, where an exponentially large variety of vacuum states and ways of compactification is available for the original 10- or 11-dimensional space. The type of compactification determines the coupling constants, the vacuum energy, the symmetry-breaking scale and, finally, the effective dimensionality of the space in which we live. As shown in ref. [25], chaotic inflation near the Planck density may lead to a local change in the number of compactified dimensions. This means that the Universe becomes divided into exponentially large parts with different dimensionality.

In some theories one may have a continuous spectrum of possibilities. For example, in the context of the Brans–Dicke theory, the effective gravitational constant is a function of the Brans–Dicke field, which also experienced fluctuations during inflation. As a result, the Universe after inflation becomes divided into exponentially large parts with all possible values of the gravitational constant G and the amplitude of density perturbations $\delta\rho/\rho$ [26, 27]. Inflation may divide the Universe into exponentially large domains with continuously varying baryon-to-photon ratio n_B/n_γ [28] and with galaxies having vastly different properties [29]. Inflation may also continuously change the effective value of the vacuum energy (the cosmological constant Λ), which is a prerequisite for many attempts to find an anthropic solution of the cosmological constant problem [6, 30–39]. Under these circumstances, the most diverse sets of parameters of particle physics (masses, coupling constants, vacuum energy, etc.) can appear after inflation. One can say that, in a certain sense, the Universe becomes a multiverse.

Recently, the multiverse scenario has attracted special attention because of the discovery that string theory admits many metastable de Sitter vacua with different properties, and different domains of the Universe may unceasingly jump between these vacua [40–42]. The lifetime of each of these states is typically much greater than the age of our part of the Universe. The total number of metastable vacuum states in string theory may be as large as 10^{1000} [43, 44].

Once this ‘string landscape’ became part of the string theory description of the world, it became very difficult to forget about it and return to the old idea that the theory must have only one vacuum state, with the goal of physics being to find it. One can either like this new picture or hate it, but it cannot be discarded purely on the basis of ideological considerations. If this scenario is correct, then physics alone cannot provide a complete explanation for all properties of our part of the Universe. The same physical theory may yield large parts of the Universe that have diverse properties. According to this scenario, we find ourselves inside a 4-dimensional domain with our

kind of physical laws, not because domains with different dimensionality and with alternate properties are impossible or improbable, but simply because our kind of life cannot exist in other domains.

This scenario provides a simple justification of the anthropic principle and removes the standard objections against it. One does not need anymore to assume that some supernatural cause created the Universe with the properties specifically fine-tuned to make our existence possible. Inflation itself, without any external intervention, may produce exponentially large domains with all possible laws of low-energy physics. And we should not be surprised that the conditions necessary for our existence appear on a very large scale rather than only in a small vicinity of the solar system. If the proper conditions are established near the solar system, inflation ensures that similar conditions appear everywhere within the observable part of the Universe.

The new possibilities that appear due to the self-reproduction of the Universe may provide a basis for what I call the ‘Darwinian’ approach to cosmology [33, 45, 46]. Mutations of the laws of physics may lead to the formation of domains with the laws of physics that allow a greater speed of expansion of the Universe; these domains will acquire greater volume and may host a greater number of observers. On the other hand, the total volume of domains of each type grows indefinitely large. This process looks like a peaceful coexistence and competition, and sometimes even like a fruitful collaboration, with the fastest growing domains producing many slower growing brothers. In the simplest models of this type, a stationary regime is reached, and the speed of growth of the total volume of domains of each type becomes equally large for all of the domains [24].

8.5 Some problems addressed by the anthropic principle

8.5.1 *The cosmological constant and dark energy*

According to the most recent data, vacuum energy (be it a cosmological constant or some other form of ‘dark energy’) with density Λ (or ρ_Λ) constitutes 74% of the total energy density of the Universe ρ_0 , dark matter with density ρ_{DM} constitutes 22% of ρ_0 , and normal matter with density ρ_{M} contributes only 4% of ρ_0 . One of the most challenging problems of theoretical physics is to explain why the vacuum energy is so small, $\Lambda \sim \rho_{\text{M}} \sim 10^{-120} M_{\text{p}}^4$, and, at the same time, why it is of the same order as the total energy density of the Universe.

The first attempt to solve the cosmological constant problem using the anthropic principle in the context of inflationary cosmology was made in ref. [6]. In this paper it was argued that, if one considers antisymmetric

tensor fields F , they give a time-independent contribution to the vacuum energy density of the Universe, depending on the value of these fields. The total vacuum energy density is given by the sum $V(\phi) + V(F)$. According to quantum cosmology, which is based on the tunnelling wave-function of the Universe, the probability of quantum creation of the Universe is $O(1)$ for $V(\phi) + V(F) \sim 1$ in units of the Planck energy density.

Consider, for example, the theory $V(\phi) = m^2\phi^2/2 + V_0$. In this case, all models emerge with equal probability at the moment when $m^2\phi^2/2 + V_0 + V(F) \sim 1$, but then the vacuum energy density in each region relaxes to $\Lambda = V_0 + V(F)$. The sum $V_0 + V(F)$ does not itself affect the probability of the quantum creation of the Universe, since all models are equally probable for $m^2\phi^2/2 + V_0 + V(F) \sim 1$. Thus one comes to the conclusion that models with all values of Λ are equally probable. It was argued [6] that life of our type can exist only in the universes with $|\Lambda| \lesssim O(10)\rho_0 \sim 10^{-28} \text{ g cm}^{-3} \sim \rho_M$, where ρ_0 is the present density in our part of the Universe and $\rho_M \sim 0.3\rho_0$ is the density of matter (including dark matter). This, together with the flat probability distribution for creation of the universes with different Λ , may solve the cosmological constant problem.

There is another way to solve the cosmological constant problem [8]. One may consider inflation driven by the scalar field ϕ (the inflaton field) and mimic the cosmological constant by the very flat potential of a second scalar field Φ . The simplest potential of this type is linear:

$$V(\Phi) = \alpha M_{\text{p}}^3 \Phi. \quad (8.6)$$

For a sufficiently small α , this potential can be so flat that the field Φ practically does not change during the last 10^{10} y, so at the present epoch its total potential energy $V(\Phi)$ acts exactly as a cosmological constant. This model was one of the first examples of what later became known as quintessence, or dark energy.

Even though the energy density of the field Φ hardly changes at the present time, it changed substantially during inflation. Since Φ is a massless field, it experienced quantum jumps with amplitude $H/(2\pi)$ during each timescale H^{-1} . These jumps moved the field Φ in all possible directions. In the context of the eternal inflation scenario, this implies that the field became randomized by quantum fluctuations. The Universe broke up into an infinite number of exponentially large parts, containing all possible values of the field Φ , i.e. into an infinite number of infinitely large ‘universes’ with different values of the effective cosmological constant $\Lambda = V(\Phi) + V(\phi_0)$, where $V(\phi_0)$ is the energy density of the inflation field ϕ in the minimum of its effective potential. This quantity may vary from $-M_{\text{p}}^4$ to $+M_{\text{p}}^4$ in different parts of the Universe,

but we can live only in universes with $|\Lambda| \lesssim O(10)\rho_0 \sim 10^{-28} \text{ g cm}^{-3}$, where ρ_0 is the present density in our part of the Universe [8].

This last statement requires an explanation. If Λ is large and negative, $\Lambda \lesssim -10^{-28} \text{ g cm}^{-3}$, the Universe collapses within a timescale much smaller than the present age of the Universe [1, 6]. On the other hand, if $\Lambda \gg 10^{-28} \text{ g cm}^{-3}$, the present Universe would expand exponentially fast, the energy density of matter would become exponentially small and life as we know it would be impossible [6, 8]. This means that we can live only in those parts of the Universe where the cosmological constant does not differ too much from its presently observed value, $|\Lambda| \sim \rho_0$.

The constraint $\Lambda \gtrsim -10^{-28} \text{ g cm}^{-3}$ still remains the strongest one for a negative cosmological constant; for recent developments related to this constraint, see refs. [37] and [39]. The constraint for a positive cosmological constant, $\Lambda \leq 10^{-28} \text{ g cm}^{-3}$, was made much more precise and accurate in subsequent works. In particular, Weinberg pointed out that the process of galaxy formation occurs only up to the moment when the cosmological constant begins to dominate the density of the Universe, after which the Universe enters the late stages of inflation [31]. For example, galaxies which formed at $z \geq 4$, when the density of the Universe was two orders of magnitude greater than it is now, would not have done so for $\Lambda \gtrsim 10^2 \rho_0 \sim 10^{-27} \text{ g cm}^{-3}$.

The next important step was made in a series of works [32–38] which considered not only our own galaxy, but also all other ones that could harbour life of our type. This would include not only galaxies formed in the past but also those forming at the present epoch. Since the density at later stages of cosmic evolution always decreases, even a very small cosmological constant may disrupt late-time galaxy formation or prevent the growth of existing galaxies. This strengthens the constraint on the cosmological constant. According to ref. [34], the probability that an astronomer in any of the universes would find the presently observed ratio Λ/ρ_0 as small as 0.7 ranges from 0.05 to 0.12, depending on various assumptions. For some models based on extended supergravity, the anthropic constraints can be strengthened even further [39].

It would be most important to obtain a solution of the cosmological constant problem in string theory. Surprisingly, despite many attempts, for a long time we did not even know how to formulate this problem, because all existing string theories were unable to describe a model with a stable vacuum and a positive cosmological constant. This problem was solved only recently [2]; we have already mentioned the solution in our discussion of the string theory landscape. The solution involved investigation of stabilized

flux vacua in string theory and suggested that there may be many different vacua with different values of Λ . An investigation of this issue demonstrated that the total number of different de Sitter vacua in string theory can be astonishingly large, of the order 10^{100} or perhaps even 10^{1000} , which created the notion of the vast string theory landscape [41–44]. Simple dimensional estimates suggest that the vacuum energy density in the stringy vacua may vary from $-O(1)$ to $+O(1)$ in Planck (or string) units. Therefore it is possible that there are many vacuum states with $|\Lambda| \sim 10^{-120}$ and that the total number of vacua has a relatively flat dependence on the energy density in this range. This would provide an anthropic solution of the cosmological constant problem in string theory.

One should emphasize an important assumption made in all of these considerations. In order to solve the cosmological constant problem, it is necessary to assume that the prior probability to have non-vanishing cosmological constants is practically independent of Λ . Indeed, if larger values of the cosmological constant were much more probable, one would conclude that we must live when $\Lambda \gg 10^{-120}$. On the other hand, if Λ has to be zero because of some symmetry, but appears due to some non-perturbative effect, then one could expect $\Lambda \sim e^{-\alpha}$ where α is some field or random parameter. If this parameter, rather than Λ , has a flat probability distribution, then the probability that $\Lambda \sim 10^{-120}$ will be as large as the probability that $\Lambda \sim 10^{-121}$ or $\Lambda \sim 10^{-1000}$. This would make it very difficult to explain the observed value of the cosmological constant.

The situation appears even worse if one calculates the probability for a given point to be in a state with a particular value of Λ , corresponding to some set of vacua. This probability is given by the square of the Hartle–Hawking wave-function:

$$P \sim \exp\left(-\frac{24\pi^2}{\Lambda}\right) = e^{-S_\Lambda}, \quad (8.7)$$

where S_Λ is the entropy of de Sitter space [47–49]. If one uses this probability, one may conclude that we must live in the state with the smallest possible value of Λ , independently of any anthropic considerations. On the other hand, one may argue that this distribution should not be used, since the probability distribution $P \sim e^{-S_\Lambda}$ is established by the continuous tunnelling back and forth between different vacua. This takes a ridiculously large time, $t \sim e^{S_\Lambda} \sim 10^{10^{120}}$ y, which is much greater than the age of the Universe. Moreover, it is not obvious that it makes any sense to consider a typical situation at a given point. Rather, one may want to try to find a typical situation in a given volume at a given time [24].

However, here we face a new problem. An eternally self-reproducing Universe consists of an indefinitely large number of regions, where all kinds of processes may occur, even if their probability is very small. To compare the total volume of the parts of the Universe with different properties, one should compare infinities, which may lead to ambiguities. Different methods of calculations produce different results [24,27,33,48,50–53]. We believe that all of these different answers are in a certain sense correct; it is the choice of the questions that remains problematic.

To explain our point of view, let us study an example related to demographics. One may want to know the average age of a person living now on the Earth. In order to find it, one should take the sum of the ages of all people and divide it by their total number. Naïvely, one would expect the result of the calculation to be half the life expectancy. However, the actual result will be much smaller. Because of the exponential growth of the population, the main contribution to the average age will be given by very young people. Both answers (the average age of a person and half the life expectancy) are correct, despite the fact that they are different. Neither answer is any better; they are different because they address different questions. Economists may want to know the average age in order to make projections, but individuals – as well as the insurance industry – may be more interested in the life expectancy.

Similarly, the calculations performed in refs. [24], [27], [33] and [50–53] dissect all possible outcomes of the evolution of the Universe (or multiverse) in many different ways. Each of these ways is legitimate and leads to correct results, but some additional input is required in order to understand which of these results, if any, is most closely related to the anthropic principle.

This ambiguity may suggest that one should abandon the anthropic principle and replace it by something more predictive. For example, Smolin has suggested that universes could be formed inside black holes. By finding the parameters which maximize the production of black holes and, consequently, the creation of new universes, one could find the set of universes favoured by evolution [54,55].

From my point of view, this suggestion is not an alternative to the anthropic principle, but a very speculative version of it, which does not offer any advantages and has a major drawback. It does not offer any advantages because the total number of black holes produced during inflation is exponentially sensitive to the duration of inflation and to the amplitude of density perturbations produced then. None of these issues have been considered in refs. [54] or [55]. In order to do so, one needs to resolve the problem of measure discussed above. The drawback of this suggestion is

the absence of any reliable theoretical description of the creation of new universes with different properties inside black holes. On the other hand, the aforementioned theory for the creation of new parts of the inflationary Universe is based on processes which are rather well understood.

If the theory of all fundamental interactions indeed possesses a plethora of different vacuum states, we should learn how to live with this new scientific paradigm. We must find out which of the questions we are asking may have an unambiguous answer and which ones are meaningless. I have a strong suspicion that, in order to answer the question of why we live in our part of the Universe, we must first learn the answers to the questions ‘What is life?’ and ‘What is consciousness?’ [13, 46, 50, 56].

Until these problems are solved, one may take a pragmatic point of view and consider this investigation as a kind of ‘theoretical experiment’. We may try to use probabilistic considerations in a trial-and-error approach. If we get unreasonable results, this may serve as an indication that we are using quantum cosmology incorrectly. However, if some particular proposal for the probability measure allows us to solve certain problems which could not be solved in any other way, then we will have a reason to believe that we are moving in the right direction.

We can also use the new cosmological paradigm in a rather modest way. For example, we may not exactly know the prior probability distribution for the cosmological constant Λ . However, if we do not feel that the assumption of a flat probability distribution near $\Lambda = 0$ is outrageous, then anthropic considerations will tell us that there is nothing outrageously unnatural in the possibility that the Universe has $\Lambda \sim 10^{-120}$ in Planck units. In other words, anthropic considerations allow us to find *possible* explanations of some facts which would otherwise look absolutely miraculous. In the next section, we will give another illustration of this way of thinking.

8.5.2 The anthropic principle and axions

Now we have a possible reason for why the vacuum density has the same order as the total matter density in the Universe, can we go further and understand why dark matter is five times more abundant than ordinary matter? Let us assume that dark matter is represented by the axion field θ , which was introduced in order to solve the problem of strong CP violation. The potential of the axion field has the following form:

$$V(\theta) \sim m_\pi^4 \left(1 - \cos \frac{\theta}{\sqrt{2} f} \right). \quad (8.8)$$

The field θ can take any value in the range $-\sqrt{2}\pi f$ to $\sqrt{2}\pi f$. A natural estimate for the initial value of the axion field would therefore be $\theta = O(f)$, and the initial value of $V(\theta)$ should be of order m_π^4 . An investigation of the rate at which the energy of the axion field ρ_θ falls off as the Universe expands shows that, for $f \gtrsim 10^{12}$ GeV, most of the energy density would presently be contributed by axions, while the baryon energy density would be considerably lower than its presently observed value of $\rho_B \sim 0.05\rho_0$. This information was used to derive the constraint $f \lesssim 10^{12}$ GeV [57–59].

This is a very strong constraint, especially since the astrophysical considerations lead to a constraint $f \gtrsim 10^{11}$ GeV. Note also that the standard scale for f in string theory is $f \sim M_p \sim 10^{18} - 10^{19}$ GeV. This means that one should construct theories with an unnaturally small value of f , and even this may not help unless the parameter f is in the very narrow ‘axion window’ $10^{11} \lesssim f \lesssim 10^{12}$ GeV.

Let us now take a somewhat closer look at whether one can actually obtain the constraint $f \lesssim 10^{12}$ GeV in the context of inflationary cosmology. Long-wave fluctuations of the axion field θ are generated during inflation if Peccei–Quinn symmetry-breaking, resulting in the potential given by Eq. (8.8), takes place before the end of inflation. By the end of inflation, therefore, a quasi-homogeneous distribution of the field θ will have appeared in the Universe, with the field taking on all values from $-\sqrt{2}\pi f$ to $\sqrt{2}\pi f$ at different points in space with a probability that is almost independent of θ . This means that one can always find exponentially large regions of space within which $\theta \ll f$. The energy of the axion field always remains relatively low in such regions and there is no conflict with the observational data.

This feature does not itself remove the constraint $f \lesssim 10^{12}$ GeV. Indeed, when $f \gg 10^{12}$ GeV, only within a very small fraction of the volume of the Universe is the axion field energy density small enough by comparison with the baryon density. It might therefore seem extremely improbable that we live in one of these particular regions.

Consider, for example, those regions initially containing a field $\theta_0 \ll f$, for which the present ratio of the energy density of the axion field to the baryon density is consistent with the observational data (i.e. where the density of dark matter is about five times greater than the baryon density). It can be shown that the total number of baryons in regions with $\theta \sim 10\theta_0$ should be ten times the number in regions with $\theta \sim \theta_0$. One might therefore expect the probability of randomly ending up in a region with $\theta \sim 10\theta_0$ (incompatible with the observational data) to be ten times that of ending up in a region with $\theta \sim \theta_0$.

However, closer examination of this problem indicates that the properties of galaxies formed in such a region should be very different from the properties of our galaxy. This makes it unclear whether life can exist in the regions with $\theta \geq 10\theta_0$ [29]. Let us compare the domains with $\theta = \theta_0$ and $\theta = N\theta_0$ at the same cosmological time t in an early universe dominated by hot matter. Since the Universe after inflation becomes flat, the total density during this post-inflationary stage is proportional to t^{-2} , practically independent of the relative fraction of matter in axions and in baryons. This has two interesting implications. The first is that at $t \sim 10^{10}$ y the total density in both domains will be the same but the baryon density will be N^2 times smaller in the domain with $\theta = N\theta_0$. In other words, in a domain with $\theta \sim 10\theta_0$, the observable region after 10^{10} y will contain one hundred times fewer baryons than a domain with $\theta \sim \theta_0$. As discussed below, this alone may reduce the probability of the emergence of life.

The second implication is related to the properties of galaxies in domains with $\theta \sim N\theta_0$. The ratio $n_B/n_\gamma \sim 10^{-10}$ is fixed by some processes in the early Universe, which are not expected to depend on the axion abundance. The main difference between the two domains discussed above is that the relative energy density of non-relativistic particles is N^2 times higher in the second domain. Also, at the same time t , the ratio of the energy density of photons and cold dark matter will be N^2 smaller, i.e. this domain is colder. The cold dark matter energy density decreases as $t^{-3/2}$, whereas the energy density of photons decreases as t^{-2} , i.e. $t^{-1/2}$ times faster. Therefore the period of cold dark matter dominance occurred N^4 times earlier in the second domain. The energy density of cold dark matter at that moment was $\sim N^8$ times higher than in the first domain.

Note that the beginning of cold dark matter dominance is the time when density perturbations $\delta\rho/\rho \sim 10^{-4}$ start growing. Since they start growing earlier, the moment when they reach $O(1)$ – i.e. the stage when overdense regions separate into galaxies – also occurs earlier. The density of matter inside galaxies in the future remains of the same order as the density of the Universe at the time of the galaxy formation. This means that the density of matter in the first (smallest) galaxies to be formed in the second domain will be N^8 higher than in the first domain, and the density of baryons there will be N^6 times higher.

The matter density in large galaxies, which formed later in the evolution of the Universe, should be less sensitive to θ . However, if most of the matter is packed into superdense dwarf galaxies formed in the very early Universe, the total amount of remaining matter – which would be distributed more smoothly like in our own galaxy – may be relatively small. Also, any

galaxy of a given mass M will contain N^2 times fewer baryons than our galaxy.

Naïvely, it would seem ten times more probable to live in domains with $\theta = 10\theta_0$ because the total volume of such domains is ten times bigger. However, since the properties of galaxies in a universe with $\theta = 10\theta_0$ are very different from those of our galaxy, it well may happen that domains with $\theta \sim \theta_0$ provide much better conditions for the emergence of life than domains with $\theta = 10\theta_0$ [29]; see also ref. [60].

In order to study this situation quantitatively, one should perform a detailed investigation of galaxy formation in a model with $\rho_M \gg \rho_B$, similar to the investigation of galaxy formation in a model dominated by a cosmological constant ($\rho_\Lambda \gg \rho_M$), as discussed in Section 8.5.1. This investigation has been performed very recently [61]. The results obtained confirmed the expectations of ref. [29]: if dark matter is represented by axions with $f \gg 10^{12}$ GeV, then one is most likely to live in a model where the density of dark matter is about one or two orders of magnitude greater than the density of ordinary matter. This is quite consistent with the observed value $\rho_{DM} \sim 5\rho_M$.

This result has two interesting implications. First, it will not be too surprising to find that the standard constraints $10^{11} \lesssim f \lesssim 10^{12}$ GeV are violated. Second, in the context of the axion cosmology with $f \gg 10^{12}$ GeV, it is not surprising that we live in a universe with $\rho_{DM} \sim 5\rho_M$. In this respect, such a theory has an important advantage with respect to many other dark matter theories, where one must fine-tune the parameters to obtain $\rho_{DM} \sim 5\rho_M$.

8.5.3 An anthropic explanation of the electroweak symmetry-breaking scale and the hierarchy problem

The situation with the Higgs boson mass and the amplitude of spontaneous symmetry-breaking in electroweak theory is even more interesting and impressive. One of the main problems of particle physics is the extremely small ratio of the Higgs field expectation value, $v \approx 246$ GeV, to the Planck mass, $M_P \approx 2.4 \times 10^{18}$ GeV. Assuming that the coupling constant λ of the Higgs boson is $O(1)$ or smaller, this leads [62] to an incredibly small ratio of the Higgs mass, $m_H \sim \sqrt{\lambda}v$, to the Planck mass: $m_H/M_P \sim v/M_P \sim 10^{-16}$.

A popular attempt to address this problem is based on supersymmetry. If supersymmetry is broken on a very small scale, then many particles, including the Higgs boson, acquire comparable masses $\sim 10^2$ GeV, and these

masses do not acquire large radiative corrections. However, this would be a true solution of the problem only if we were able to understand the origin of the anomalously small scale of supersymmetry-breaking.

The anthropic principle allows one to look at this problem from a different point of view. Agrawal and colleagues [63, 64] have shown that all nuclei would be unstable for v five times larger than observed, whereas protons would be unstable and hydrogen would not exist for v less than half the observed value. This explains the origin of the ratio $m_H/M_p \sim 10^{-16}$.

The strongest anthropic constraints on the scale of spontaneous symmetry-breaking v can be obtained if one studies production of carbon and oxygen in the Universe [64]. These two elements are formed during helium-burning at late stages of stellar evolution. As noted by Hoyle and colleagues [65, 66], this process depends crucially on the existence of a certain resonance level in carbon nuclei. The existence and properties of this resonance was one of the first successful predictions based on the anthropic principle. However, these properties depend on the quark masses, which in turn depend on v . This leads to strong anthropic constraints on v .

This question has been studied by many authors, for example Livio *et al.* [67] and Hogan [68]. The most detailed investigation was carried out by Oberhummer *et al.* [69, 70], Jeltama and Sher [71] and Schlattl *et al.* [72]. They found that a change of v by 1% would lead to a strong suppression of the production of carbon (if v were smaller than 246 GeV) or oxygen (if v were greater than 246 GeV). Since both carbon and oxygen are necessary for our existence, this result strongly indicates that the otherwise unexplained value of v , as well as the small number m_H/M_p , can be determined by anthropic considerations. (The accuracy of this determination is much better than that with which the anthropic principle fixes the value of the cosmological constant Λ .)

If this is the case, supersymmetry is not required to explain the smallness of the Higgs boson mass. If this is small because of anthropic considerations, supersymmetry may become manifest at much higher energies, as suggested by Arkani-Hamed and colleagues [73, 74]. This may have important implications for attempts to find supersymmetry at the Large Hadron Collider (LHC). The main motivation for these attempts was the standard idea that there should be many supersymmetric particles with masses similar to the Higgs boson mass. This idea has guided theoretical investigations for the last twenty years, and the total cost of the experimental search for low-energy supersymmetry is billions of dollars. Thus, as in the case of the axion search, ignoring anthropic considerations can be expensive.

If no light supersymmetric particles are found at LHC, it will be an additional argument in favour of anthropic reasoning. On the other hand,

anthropic arguments do not preclude low-energy SUSY-breaking. If light supersymmetric particles *were* discovered at LHC, then it would imply that SUSY is indeed broken at the low-energy scale associated with the Higgs mass. But since the Higgs mass can itself be explained by anthropic considerations, the discovery of light supersymmetric particles may imply that the low scale of SUSY-breaking also has an anthropic explanation.

8.6 Conclusions

For a long time physicists have believed that there is only one world and that a successful description of this world should eventually predict all of its parameters, such as the coupling constants and the masses of elementary particles. The fundamental theory was supposed to be beautiful and natural. This was a noble, but perhaps excessively optimistic, hope. One could call this period ‘the age of innocence’.

I believe we are now entering ‘the age of anthropic reasoning’. Inflationary cosmology – in combination with string theory – leads to a picture of a multiverse consisting of an infinite number of exponentially large domains (‘universes’) with an exponentially large number of different properties. In addition to a somewhat subjective notion of beauty and naturalness, we are adding the simple and obvious criterion that the part of the Universe where we live must be consistent with the possibility of our existence. This super-selection rule sometimes considerably improves our intuitive judgement about what is natural. For example, naïvely, the most natural scale for the Higgs boson mass is $O(M_p)$ and the most natural value of the vacuum energy density is $O(M_p^4)$. However, it is unnatural and in fact impossible for us to live in a universe (or even part of a universe) with such parameter values. In a certain sense, one may consider anthropic reasoning as a way to improve the naïve use of the concept of naturalness.

The concept of beauty may also play an important role in the selection of the vacuum state. One possible idea is that symmetry implies that the properties of the world do not change under certain transformations. This may mean that, if one can live in a given vacuum state, one can live in a whole family of states related to each other by symmetry. The existence of many equivalent states may increase the probability of living in one of them, by effectively increasing the phase volume of the anthropically allowed vacua possessing the symmetry. In addition, states with large symmetry (i.e. beauty) are sometimes dynamically attractive, behaving as trapping points in the space of all possible vacua [75]. In this way, one may try to unify anthropic reasoning with the principles of naturalness and beauty, which have always guided our search for the fundamental theory describing our world.

References

- [1] J. D. Barrow and F. J. Tipler. *The Anthropic Cosmological Principle* (New York: New York University Press, 1986).
- [2] I. L. Rozental. *Big Bang, Big Bounce* (New York: Springer Verlag, 1988).
- [3] M. Rees. *Just Six Numbers, The Deep Forces that Shape the Universe* (New York: Basic Books, Perseus Group, 2000).
- [4] A. D. Linde. Non-singular regenerating inflationary universe. Cambridge University preprint-82-0554 (1982).
- [5] A. D. Linde. The new inflationary universe scenario. In *The Very Early Universe*, eds. G. W. Gibbons, S. W. Hawking and S. Siklos (Cambridge: Cambridge University Press, 1983), pp. 205–49.
- [6] A. D. Linde. The inflationary universe. *Rep. Prog. Phys.* **47** (1984), 925.
- [7] A. D. Linde. Eternally existing self-reproducing chaotic inflationary universe. *Phys. Lett.* **B 175** (1986), 395.
- [8] A. A. Starobinsky. A new type of isotropic cosmological model without singularity. *Phys. Lett.* **B 91** (1980), 99.
- [9] A. H. Guth. (1981) The inflationary universe: a possible solution to the horizon and flatness problems. *Phys. Rev.* **D 23** (1981), 347.
- [10] A. D. Linde. A new inflationary universe scenario: a possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems. *Phys. Lett.* **B 108** (1982), 389.
- [11] A. D. Linde. Chaotic inflation. *Phys. Lett.* **B 129** (1983), 177.
- [12] A. Albrecht and P. J. Steinhardt. Cosmology for grand unified theories with radiatively induced symmetry breaking. *Phys. Rev. Lett.* **48** (1982), 1220.
- [13] A. D. Linde. *Particle Physics and Inflationary Cosmology* (Chur, Switzerland: Harwood Academic Publishers, 1990).
- [14] A. D. Linde. Inflation can break symmetry in SUSY. *Phys. Lett.* **B 131** (1983), 330.
- [15] A. Vilenkin and L. H. Ford. Gravitational effects upon cosmological phase transitions. *Phys. Rev.* **D 26** (1982), 1231.
- [16] A. D. Linde. Scalar field fluctuations in expanding universe and the new inflationary universe scenario. *Phys. Lett.* **B 116** (1982), 335.
- [17] V. F. Mukhanov and G. V. Chibisov. Quantum fluctuation and ‘non-singular’ universe. *JETP Lett.* **33** (1981), 532. (*Pisma Zh. Eksp. Teor. Fiz.* **33** (1981), 549).
- [18] S. W. Hawking. The development of irregularities in a single bubble inflationary universe. *Phys. Lett.* **B 115** (1982), 295.
- [19] A. A. Starobinsky. Dynamics of phase transition in the new inflationary universe scenario and generation of perturbations. *Phys. Lett.* **B 117** (1982), 175.
- [20] A. H. Guth and S. Y. Pi. Fluctuations in the new inflationary universe. *Phys. Rev. Lett.* **49** (1982), 1110.
- [21] J. M. Bardeen, P. J. Steinhardt and M. S. Turner. Spontaneous creation of almost scale-free density perturbations in an inflationary universe. *Phys. Rev.* **D 28** (1983), 679.
- [22] P. Steinhardt. Natural inflation. In *The Very Early Universe*, eds. G. W. Gibbons, S. W. Hawking and S. Siklos (Cambridge: Cambridge University Press, 1983).
- [23] A. Vilenkin. The birth of inflationary universes. *Phys. Rev.* **D 27** (1983), 2848.

- [24] A. D. Linde, D. A. Linde and A. Mezhlumian. From the big bang theory to the theory of a stationary universe. *Phys. Rev. D* **49** (1994), 1783 [gr-qc/9306035].
- [25] A. D. Linde and M. I. Zelnikov. Inflationary universe with fluctuating dimension. *Phys. Lett. B* **215** (1988), 59.
- [26] A. D. Linde. Extended chaotic inflation and spatial variations of the gravitational constant. *Phys. Lett. B* **238** (1990), 160.
- [27] J. Garcia-Bellido, A. D. Linde and D. A. Linde. Fluctuations of the gravitational constant in the inflationary Brans–Dicke cosmology. *Phys. Rev. D* **50** (1994), 730 [astro-ph/9312039].
- [28] A. D. Linde. The new mechanism of baryogenesis and the inflationary universe. *Phys. Lett. B* **160** (1985), 243.
- [29] A. D. Linde. Inflation and axion cosmology. *Phys. Lett. B* **201** (1988), 437.
- [30] A. D. Linde. Inflation and quantum cosmology. In *Three Hundred Years of Gravitation*, eds. S. W. Hawking and W. Israel (Cambridge: Cambridge University Press, 1987), pp. 604–30.
- [31] S. Weinberg. Anthropic bound on the cosmological constant. *Phys. Rev. Lett.* **59** (1987), 2607.
- [32] G. Efstathiou. An anthropic argument for a cosmological constant. *Mon. Not. Roy. Astron. Soc.* **274** (1995), L73.
- [33] A. Vilenkin. Predictions from quantum cosmology. *Phys. Rev. Lett.* **74** (1995), 846 [gr-qc/9406010].
- [34] H. Martel, P. R. Shapiro and S. Weinberg. Likely values of the cosmological constant. *Astrophys. J.* **492** (1998), 29 [astro-ph/9701099].
- [35] J. Garriga, and A. Vilenkin. On likely values of the cosmological constant. *Phys. Rev. D* **61** (2000), 083502 [astro-ph/9908115].
- [36] J. Garriga and A. Vilenkin. Solutions to the cosmological constant problems. *Phys. Rev. D* **64** (2001), 023517 [hep-th/0011262].
- [37] J. Garriga and A. Vilenkin. Testable anthropic predictions for dark energy. *Phys. Rev. D* **67** (2003), 043503 [astro-ph/0210358].
- [38] S. A. Bludman and M. Roos. Quintessence cosmology and the cosmic coincidence. *Phys. Rev. D* **65** (2002), 043503 [astro-ph/0109551].
- [39] R. Kallosh and A. D. Linde. M-theory, cosmological constant and anthropic principle. *Phys. Rev. D* **67** (2003), 023510 [hep-th/0208157].
- [40] S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi. De Sitter vacua in string theory. *Phys. Rev. D* **68** (2003), 046005 [hep-th/0301240].
- [41] L. Susskind. This volume (2007) [hep-th/0302219].
- [42] L. Susskind. *The Cosmic Landscape, String Theory and the Illusion of Intelligent Design* (New York: Little, Brown and Company, 2006).
- [43] R. Bousso and J. Polchinski. Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. *JHEP*, **0006** (2000), 006 [hep-th/0004134].
- [44] M. R. Douglas. The statistics of string/M theory vacua. *JHEP*, **0305** (2003), 046 [hep-th/0303194].
- [45] A. D. Linde. Particle physics and inflationary cosmology. *Physics Today*, **40** (1987), 61.
- [46] J. Garcia-Bellido and A. D. Linde. Stationarity of inflation and predictions of quantum cosmology. *Phys. Rev. D* **51** (1995), 429 [hep-th/9408023].
- [47] S. W. Hawking. The cosmological constant is probably zero. *Phys. Lett. B* **134** (1984), 403.

- [48] A. A. Starobinsky. Stochastic de Sitter (inflationary) stage in the early universe. In *Current Topics in Field Theory, Quantum Gravity and Strings*, eds. H. J. de Vega and N. Sanchez (Heidelberg: Springer, 1986), p. 107.
- [49] A. D. Linde. Quantum creation of an open inflationary universe. *Phys. Rev. D* **58** (1998), 083514 [gr-qc/9802038].
- [50] A. D. Linde and A. Mezhlumian. On regularization scheme dependence of predictions in inflationary cosmology. *Phys. Rev. D* **53** (1996), 4267 [gr-qc/9511058].
- [51] V. Vanchurin, A. Vilenkin and S. Winitzki. Predictability crisis in inflationary cosmology and its resolution. *Phys. Rev. D* **61** (2000), 083507 [gr-qc/9905097].
- [52] J. Garriga and A. Vilenkin. A prescription for probabilities in eternal inflation. *Phys. Rev. D* **64** (2001), 023507 [gr-qc/0102090].
- [53] M. Tegmark. What does inflation really predict? *J. Cosmol. Astropart. Phys.*, **0504** (2005), 001 [astro-ph/0410281].
- [54] L. Smolin. *The Life of the Cosmos* (New York: Oxford University Press, 1997).
- [55] L. Smolin. This volume (2007).
- [56] A. D. Linde, D. A. Linde and A. Mezhlumian. Non-perturbative amplifications of inhomogeneities in a self-reproducing universe. *Phys. Rev. D* **54** (1996), 2504 [gr-qc/9601005].
- [57] J. Preskill, M. B. Wise and F. Wilczek. Cosmology of the invisible axion. *Phys. Lett. B* **120** (1983), 127.
- [58] L. F. Abbott and P. Sikivie. A cosmological bound on the invisible axion. *Phys. Lett. B* **120** (1983), 133.
- [59] M. Dine and W. Fischler. The not-so-harmless axion. *Phys. Lett. B* **120** (1983), 137.
- [60] F. Wilczek. This volume (2007) [hep-ph/0408167].
- [61] M. Tegmark, A. Aguirre, M. Rees and F. Wilczek. Dimensionless constants, cosmology and other dark matters. *Phys. Rev. D* **73** (2006), 023505 [astro-ph/0511774].
- [62] J. F. Donoghue. This volume (2007).
- [63] V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel. The anthropic principle and the mass scale of the standard model. *Phys. Rev. D* **57** (1998), 5480.
- [64] V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel. Anthropic considerations in multiple-domain theories and the scale of electroweak symmetry breaking. *Phys. Rev. Lett.* **80** (1998), 1822 [hep-ph/9801253].
- [65] F. Hoyle, D. N. F. Dunbar, W. A. Wenzel and W. Whaling. A state in C^{12} predicted from astronomical evidence. *Phys. Rev.* **92** (1953), 1095.
- [66] F. Hoyle. On nuclear reactions occurring in very hot stars: synthesis of elements from carbon to nickel. *Astrophys. J. Suppl.* **1** (1954), 121.
- [67] M. Livio, D. Hollowell, A. Weiss and J. W. Truran. The anthropic significance of the existence of an excited state of ^{12}C . *Nature* **340** (1989), 281.
- [68] C. J. Hogan. Why the universe is just so. *Rev. Mod. Phys.*, **72** (2000), 1149 [astro-ph/9909295].
- [69] H. Oberhummer, A. Csoto, and H. Schlattl. Stellar production rates of carbon and its abundance in the universe. *Science*, **289** (2000), 88 [astro-ph/0007178].

- [70] H. Oberhummer, A. Csoto and H. Schlattl. Bridging the mass gaps at $A=5$ and $A=8$ in nucleosynthesis. *Nucl. Phys. A* **689** (2001), 269 [nucl-th/0009046].
- [71] T. S. Jeltema and M. Sher. Triple-alpha process and the anthropically allowed values of the weak scale. *Phys. Rev. D* **61** (2000), 017301.
- [72] H. Schlattl, A. Heger, H. Oberhummer, T. Rauscher and A. Csoto. Sensitivity of the C and O production on the 3-alpha rate. *Astrophys. Space Sci.* **291** (2004), 27 [astro-ph/0307528].
- [73] N. Arkani-Hamed and S. Dimopoulos. Supersymmetric unification without low energy supersymmetry and signatures for fine-tuning at the LHC. *JHEP*, **0506** (2005), 073 [hep-th/0405159].
- [74] N. Arkani-Hamed, S. Dimopoulos, G. F. Giudice and A. Romanino. Aspects of split supersymmetry. *Nucl. Phys. B* **709** (2005), 3 [hep-ph/0409232].
- [75] L. Kofman, A. Linde, X. Liu, A. Maloney, L. McAllister and E. Silverstein. Beauty is attractive: moduli trapping at enhanced symmetry points. *JHEP*, **0405** (2004), 030 [hep-th/0403001].

9

A model of anthropic reasoning: the dark to ordinary matter ratio

Frank Wilczek

Department of Physics, Massachusetts Institute of Technology

9.1 Methodology and anthropic reasoning

There are good reasons to view attempts to deduce basic laws of matter from the existence of mind with scepticism.¹ Above all, it seems gratuitous. Physicists have done very well indeed at understanding matter on its own terms, without reference to mind. We have found that the governing principles take the form of abstract mathematical equations of universal validity, which refer only to entities – quantum fields – that clearly do not have minds of their own. Working chemists and biologists, for the most part, are committed to the programme of understanding how minds work under the assumption that it will turn out to involve complex orchestration of the building blocks that physics describes [1]; and while this programme is by no means complete, it has not encountered any show-stopper and it is supporting steady advances over a wide front. Computer scientists have made it plausible that the essence of mind is to be found in the operation of algorithms that in principle could be realized within radically different physical embodiments (cells, transistors, tinkertoys) and in no way rely on the detailed structure of physical law [2].

To put it shortly, the emergence of mind does not seem to be the sort of thing we would like to postulate and use as a basic explanatory principle. Rather, it is something we would like to understand and explain by building up from simpler phenomena. So there is a heavy burden to justify use of anthropic reasoning in basic physics. And yet there are, it seems to me, limited, specific circumstances under which such reasoning can be correct, unavoidable and clearly appropriate.

¹ By ‘basic’ I mean irreducible and I am consciously avoiding the loaded term ‘fundamental’. No doubt there are extremely profound insights about how complex systems behave and develop to be derived from the existence of mind, and in particular from its concrete emergence in history. Such insights will be fundamental by any reasonable standard, but not basic in the sense used here.

Here is a simple, but I think instructive and far from trivial, example. Why is Earth at the distance it is from the Sun? At one time (for example, to Kepler) the size and shape of the Solar System – as yet not clearly distinguished from the cosmos as a whole – might have seemed like a major question for physics, that one might hope would have a unique answer closely related to basic principles. Now, of course, the question appears quite different. We know that the Universe contains many broadly similar systems with planets orbiting around stars. We know that such systems come in various sizes and shapes, and that their structure depends sensitively on details of the complicated conditions under which they formed. We can be confident of all these assertions because they emerge from a rich background involving astronomical observations, the success of Newtonian mechanics and modern developments in cosmology and chaos theory. Given the two key features of many independent realizations and effectively random variation over the realizations, we cannot address our question in the context of planets in general, or universal laws. If we are going to address it at all, we have to refer specifically to Earth; and what makes Earth special, in this context, is that it is where we, the question-askers, find ourselves. Once we accept this starting point, we can go on to have an edifying discourse about why life would be difficult if the distance from the Earth to the Sun were quite different. We can even imagine that normal, testable scientific predictions will emerge from this discourse about where we will find life in other planetary systems – or even elsewhere in our own.

A psychological weakness of this example is that we have come a long way since Kepler's time, and it is hard to put ourselves back in the frame of mind to regard the Earth–Sun distance as a serious question for physics; but however we regard the question, it seems clear that the final step in a serious answer must involve anthropic reasoning.

The main thing I want to do here is to demonstrate that there is a choice of assumptions that, while somewhat speculative, lie well within the mainstream of present-day ideas about basic physics and cosmology, which leads to a situation whose logical structure is quite similar to this simple example, but where the question that is addressed by anthropic reasoning is one that is open, topical and widely believed to be basic. I speak of the question of the ratio r of axion dark matter to baryon matter in cosmology. To be specific, I will demonstrate, given certain reasonably conventional *physical* assumptions, the following: that r varies over the ensemble of effective homogeneous universes within a spatially gigantic multiverse that is inhomogeneous on superhorizon scales; that its variation is random (with a well characterized, non-singular measure); and – an important

refinement – that it varies essentially independently of other parameters. If we measure the probability by volume, we find that overly large values of r are most probable, but if we measure by number of potential observers, this conclusion is changed. It appears instead that the observed value of r is at least qualitatively, and perhaps semi-quantitatively, in accord with what these ideas suggest. That is intriguing, because – according to alternative, more conventional, ideas about r – the numerator and denominator arise from widely different physical causes and depend upon widely different parameters, so it has appeared as something of a mystery why the observed value is near unity. There are several additional implications of the assumptions that can be explored in future experiments.

The possibility of avoiding the bound that arises in conventional axion cosmology by having a small misalignment after inflation was mentioned in the earliest papers in axion cosmology in refs. [3–5]. It was exploited in the context of a specific inflationary cosmology in ref. [6], where the variation in the axion dark matter to baryon density ratio over different regions of the Universe was noted. Anthropic considerations were brought into the discussion in ref. [7]. Some constraints on the scenario, due to the axion field supplying an additional source of fluctuations, were derived in ref. [8].

9.2 Conventional and unconventional axion cosmology

I now very briefly review the relevant aspects of axion physics and cosmology.

9.2.1 *Axion physics*

Quantum chromodynamics (QCD) is well established as the basic (and fundamental) theory of the strong interaction [9]. When we combine QCD with the electroweak interactions, however, a subtle but I believe quite profound puzzle arises. (For reviews of axion physics, see refs. [10] and [11].) The general principles that define QCD – relativistic quantum field theory and gauge symmetry – specify its structure extremely tightly. The continuously adjustable parameters of the theory are a single overall coupling constant, a mass for each quark and one other much more obscure parameter, the so-called θ parameter. Mountains of data described by QCD precisely determine and vastly overdetermine the coupling and masses, and the description it affords is more than satisfactory.

Amidst this otherwise splendid party, the θ parameter appears as an empty chair, an invited guest whose absence is cause for concern. The θ parameter is a periodic variable whose possible values range from 0 to 2π .

It specifies the phase $e^{i\theta}$ which accompanies the occurrence of special topological features in the colour gluon field. One measure of its subtlety is that θ cannot be detected in perturbation theory. Under space inversion (P) or time reversal (T) it changes sign, so that for $\theta \neq 0$ or π these symmetries are violated. There are very stringent experimental constraints on P or (especially) T violation in the strong interaction, especially from the upper limit on the neutron's electric dipole moment. They indicate $|\theta| \leq 10^{-8}$. (The possibility that θ is near π requires separate consideration, but is excluded on other grounds.) If we were to regard QCD in isolation, we could simply impose P or T symmetry, thus naturally enforcing $\theta = 0$. But in a complete world-theory we must acknowledge that P and T are not exact symmetries of the world, and we cannot invoke them to justify $\theta = 0$. We must look for another way of explaining the smallness of θ .

Peccei and Quinn (PQ) introduced the idea that there is a special sort of approximate symmetry, valid asymptotically at short distances, that could be used to address this challenge. The PQ symmetry transformations allow translations of θ . If the symmetry were exact, all values of θ would be physically equivalent, and of course they would all preserve P and T for the strong interaction (some field redefinitions might be required to make the symmetries manifest). In reality, PQ symmetry must be spontaneously broken, since in its unbroken form it is inconsistent with non-zero quark masses. To capture this dynamics, we introduce a complex scalar order parameter field ϕ . The average value $\langle \phi \rangle$ will vanish when PQ symmetry is unbroken, but will take the form $\langle \phi \rangle = F e^{i\theta} \equiv F e^{ia/F}$ in the unbroken phase. Here F is another scalar field, whose kinetic energy is inherited from that of ϕ and normalized in the canonical way. Furthermore, PQ symmetry is not exact, but only asymptotic, even before its spontaneous breakdown. The potential for ϕ is presumably of the general form $(|\phi|^2 - F^2)^2$ in the amplitude direction, but depends on the phase only through non-perturbative effects in QCD, in roughly the form $(1 - \cos \theta) \Lambda^4$, where $\Lambda \sim 200$ MeV is roughly the QCD scale, here assumed to be much less than F . The PQ symmetry is responsible for this structure. There is a difference in energy densities of order Λ^4 as one varies over the range of θ . The minimum energy occurs very near $\theta = 0$. The scalar field a will tend to relax to zero, thus rendering $\theta = 0$ and solving our puzzle.

The field a introduced in this way is called the axion field, and of course its quanta are called axions. The phenomenology of axions is essentially controlled by the parameter F , which specifies the amplitude of the condensate; F has dimensions of mass. The mass $m_a = \Lambda^2/F$ of the axion and the strength of its basic couplings to matter are both proportional

to $1/F$. Various laboratory and phenomenological constraints appear to require $F \geq 10^9$ GeV; the axion must be both extremely light and extremely weakly coupled.

9.2.2 Standard axion cosmology

Now let us consider the cosmological implications [3–5]. PQ symmetry is unbroken at temperatures $T \gg F$. When the symmetry breaks, the initial value of the phase, that is $e^{ia/F}$, is random beyond the then-current particle horizon scale. One can analyze the fate of these fluctuations by solving the equations for a scalar field in an expanding universe. The only unusual feature is that the effective mass of the axion field depends on temperature. The axion mass is very small for $T \gg \Lambda$, even relative to its zero-temperature value, because the non-perturbative QCD effects that generate it involve coherent gluon field fluctuations (instantons) which are suppressed at high temperature. It saturates, of course, for $T \ll \Lambda$. The full temperature dependence of the mass can be pretty reliably estimated, although the necessary calculations are technically demanding.

From standard treatments of scalar fields in an expanding universe, we learn that there is an effective cosmic viscosity, which keeps the field frozen so long as the expansion parameter is large compared to the mass, $H \equiv \dot{R}/R \gg m$. In the opposite limit, $H \ll m$, the field undergoes lightly damped oscillations, which result in an energy density that decays as $\rho \propto 1/R^3$. At intermediate times there is a period of quasi-adiabatic damping. This damping has a consequence that is very important for the present discussion, namely that the final mass density, normalized to the ambient T^3 , varies roughly proportional to $F\theta^2$. The qualitative feature, that the final density decreases with decreasing F , may appear paradoxical, since the axions are getting heavier, but it is not hard to understand heuristically. For smaller values of F , corresponding to larger mass, the temperature at which the axion field begins to feel the effect of cosmic viscosity sets in earlier, and there are more damping cycles. However, the initial energy density depends only on the mismatch angle θ and is independent of F . The time-oscillating field can be interpreted as pressureless matter or dust (note that spatial inhomogeneities on small scales, which would provide pressure, begin to be damped as they enter the horizon). In simple words, we can say that the initial misalignment in the axion field, compared with what later turns out to be the favoured value, relaxes by emission of axions in a very cold coherent state, or Bose–Einstein condensate. It is *not* in thermal equilibrium

with ordinary matter; the interactions are far too weak to enforce that equilibrium.

If we ignore the possibility of inflation, then – for the large values of F of interest – the horizon scale at the PQ transition at $T \approx F$ corresponds to a spatial region today that is negligibly small on cosmological scales. Thus, in calculating the axion density we are justified in performing an average over the initial mismatch angle. This allows us to calculate a unique prediction for the density, given the microscopic model. The result of the calculation is usually quoted in the following form:

$$\rho_{\text{axion}}/\rho_{\text{dark}} \approx F/(10^{12} \text{ GeV}), \quad (9.1)$$

where ρ_{dark} is the dark energy density. In this way, we would deduce that axions form a good dark matter candidate for $F \sim 10^{12} \text{ GeV}$ and that larger values of F are forbidden. These conclusions are unchanged if we allow for the possibility that an epoch of inflation preceded the PQ transition.

9.2.3 *Alternative axion cosmology*

Things are very different, however, if inflation occurs after the PQ transition [12].² For then, the effective Universe accessible to present-day observation, instead of containing many horizon-volumes from the time of the PQ transition, is contained well within just one. It is therefore not appropriate to average over the initial mismatch angle. We have to restore it as a *contingent universal constant*. That is, it is a pure number that characterizes the observable Universe as a whole, but which clearly cannot be determined from any more basic quantities, even in principle – indeed it is a different number elsewhere in the multiverse!

In that case, it is appropriate to replace Eq. (9.1) by:

$$r \equiv \rho_{\text{axion}}/\rho_{\text{baryon}} \approx 12 \left(\frac{F}{10^{12} \text{ GeV}} \right) \sin^2(\theta/2). \quad (9.2)$$

This differs from the earlier form in that I have normalized the axion density relative to baryon density rather than dark matter density. This change is completely trivial at a numerical level, of course. (For concreteness, I have taken $\rho_{\text{dark}}/\rho_{\text{baryon}} = 6$.) It reflects, however, two important ideas. First, changes in the mismatch angle θ do not significantly affect baryogenesis, so that the baryon density is a fixed proportion of the photon density at high temperature, and provides an appropriate gauge for measuring the

² The logical possibility of axion cosmology based on that large F and small initial mismatch in inflationary cosmology has been known since the publication of ref. [3]. The present discussion extends a portion of ref. [12].

aspects of the cosmic environment apart from F and θ . This is true in many, but perhaps not all, plausible models of baryogenesis. Second, I have reinstated the θ dependence. The exact formula for this dependence is more complicated, but Eq. (9.2) has the correct qualitative features.

In this alternative axion cosmology, values of $F \geq 10^{12}$ GeV are no longer necessarily inconsistent with existing observations. An ‘over-large’ value of F can be compensated for by a small value of the initial mismatch θ .

9.3 Application of anthropic reasoning

In the alternative axion cosmology, r – through its dependence on the initial mismatch θ – becomes a contingent universal constant. Furthermore, it varies in a statistically well categorized manner over the multiverse; its variation can be considered in isolation from possible changes in other universal constants; and it has significant impact upon the possible emergence of intelligent observers. Altogether it appears to be an ideally favourable case for the application of anthropic reasoning.

Since in practice we only get to sample one effective universe, there is no question of checking statements about the probability distribution of effective universes by normal sampling methods. The best we can do is to calculate the probability that the outcome fits what we observe, given some measure. In our problem, one possible measure that suggests itself is simply unit weight per unit volume within the multiverse, corresponding to the question: what does an average place look like? Another possible measure is unit weight per unit observer within the multiverse, corresponding to the question: what does an average observer observe? The first (measure V) is quite straightforward, in our immediate case, while the second (measure A, for anthropic) involves challenging issues, both practical and conceptual. Can we really tell which parameters support the emergence of observers, much less calculate how many? Do vastly more observers later count as much as relatively few today?³ Should we really try to estimate the number of intelligent entities with distinct ‘selves’ who actually form the notions of dark matter and baryons and measure r – or what?

Here I will briefly indicate a few key issues and tentative conclusions. A more definitive treatment can be found in ref. [13]. First, we consider the

³ This dynamic question, it seems to me, is especially relevant to anthropic reasoning about the dark energy. Universes with a smaller value of the effective cosmological term can support intelligent life for longer, and – plausibly – populations of intelligent life, once established, grow exponentially. It arises even for measure V: should we take spatial volume, spacetime volume, or something else?

situation with respect to measure V. If we define $F_R \sim 10^{12}$ GeV to be the value of F that leads to the observed dark matter density in the reference cosmology, then the probability of observing less than or equal to the density we do is, taking the $\sin^2(\theta/2)$ dependence literally, given by

$$L \equiv \frac{2}{\pi} \sin^{-1} \sqrt{\frac{F_R}{2F}}, \quad (9.3)$$

while the probability of seeing more is one minus this. Note that any $F \geq F_R/2$ is allowed at some level, so that F could even be slightly smaller than F_R . We might claim victory, following measure V, if neither of these probabilities is terribly small. For $F/F_R = 10^2, 10^4, 10^6$ (the latter two roughly representing the unification and Planck scales, respectively), we find $L = 0.045, 0.0045, 0.00045$. Viewed this way, really large values of F look unlikely.

Things appear quite different from the perspective of measure A. For a first pass, I will suppose that the number of observers is proportional to the number of baryons. In the relevant part of universal history, when the cosmological term is subdominant or nearly so, the baryon density at a fixed Hubble parameter – or, to an adequate approximation, fixed age of the Universe – depends on r as $\rho_b/(\rho_a + \rho_b) = 1/(1+r)$. Using Eq. (9.2), the probability that r is equal to or less than s , according to measure A, is then given by

$$L(s, u) = \frac{\int_0^w 1/(1 + 12u \sin^2 \phi) d\phi}{\int_0^{\pi/2} 1/(1 + 12u \sin^2 \phi) d\phi}, \quad (9.4)$$

with $w \equiv \sin^{-1} \sqrt{s/(12u)}$ and $u \equiv F/F_R$. Half the probability is covered by $r \leq 1$, but there is plenty of weight around $r = 6$, even for very large values of F . The probability that r lies between 2 and 10 is very nearly 20%, whether u is 10 or 10^6 !

Both very large and very small values of r may not be smart places to live [13]. At large r , it becomes difficult to make stars: in these baryon-poor universes the largest objects that cool and fragment, as opposed to relaxing into diffuse virial clouds, are too small to make stars efficiently. At small r , we have baryon-dominated universes, and we get Silk damping and slow growth of structure. These effects (and others) are hard to survey with confidence, at least for me; but I think they can only make a pretty good situation better. Indeed, we know everything works out nicely for r a little bigger than unity, so in that range we saturate the preceding estimate; these other complications will mainly suppress the competition.

9.4 Implications

The assumptions underlying the alternative axion cosmology I have pursued above have significant implications for axion physics, supersymmetry and cosmology. By pursuing these implications, we might be able either to enhance the credibility of their application to describe reality or to demolish that credibility.

Let us first consider axion physics. Laboratory searches for solar axions within the ‘astrophysical window’, or for cosmic background axions as dark matter, have been predicated on smaller values of F than assumed here. Large values of F imply weaker coupling to matter and render direct detection more difficult. So, unfortunately, the anthropically interesting scenario is incompatible with direct detection of axions in the foreseeable future. Of course, I would be quite happy to see it ruled out in this particular way! On the other hand, large values of F would appear to have some theoretical advantages. It might be possible to identify the PQ scale with the scale of gauge symmetry unification indicated by the successful calculation of the running of the coupling constants, for example. Independent of any particular model, the general idea that a single condensate might trigger breaking of several symmetries is quite attractive. There is also some advantage to having inflation occur after PQ symmetry-breaking, in that axion strings, which certainly complicate and might ruin the cosmology of axion dark matter, are diluted away.

Let us next consider supersymmetry. If axions dominate the dark matter density, then of course the dark matter candidate that arises in many models of low-energy supersymmetry does not. This candidate is often referred to interchangeably as the WIMP (weakly interacting massive particle) or the LSP (lightest supersymmetric particle), but it is convenient here to make a distinction. The framework in which the properties of LSP/WIMP particles are discussed is most often, either explicitly or in effect, the minimal supersymmetric extension of the Standard Model. In that framework, the lightest R -parity odd particle, the LSP, is stable on cosmological timescales, and for an otherwise plausible range of parameters – notoriously, several of the phenomenologically crucial parameters in models of low-energy supersymmetry are at present poorly constrained – one finds that it is indeed a weakly interacting particle whose density is predicted, in big bang cosmology, to be compatible with what astronomers find for dark matter. So the LSP can provide the cosmological WIMP. On the other hand, even within this framework there is an equally plausible range of parameters such that the LSP is produced with too small a density to provide the cosmological WIMP. The scenario discussed above therefore favours that range.

Along this line, if we accept the approximate equality of supersymmetric dark matter to baryonic matter as a *fait accompli* arising from a coincidence among disparate microscopic parameters, say, for concreteness, $\rho_{\text{LSP}}/\rho_{\text{baryon}} = 3$, then our anthropic scenario would at least make the additional coincidence $\rho_{\text{axion}}/\rho_{\text{baryon}} = 3$ appear less conspiratorial.

Another possibility, which I find especially intriguing and not at all implausible, is that the lightest supersymmetric particle is *not* the partner of a Standard Model particle. It could be the gravitino, the dilatino, the axino, a modulino or a combination of these. In these cases, the true LSP is generally a very feebly interacting particle, with coupling strength similar to a graviton, axion, etc. The pseudo-LSP that will be observed (at the LHC, presumably) as a Standard Model partner will decay into this true LSP. The decay will be rapid on cosmological timescales, so the pseudo-LSP sort of WIMP cannot supply the cosmological dark matter. Since the true LSP is very feebly interacting and relatively light, direct production of the true LSP during the big bang will not yield a cosmologically significant density of dark matter. It might be produced at a cosmologically significant level at relatively late times through decays of the pseudo-LSP, but it requires some special adjustments both to avoid wreaking cosmological havoc with these decays and to reproduce the observed dark matter abundance.

It is at least equally plausible to suppose that LSPs are not produced enough to make the observed dark matter, and that is an important independent motivation to consider axions as an alternative. An especially spectacular possibility is that the pseudo-LSP might be electrically charged. Cosmologically stable charged matter in the form of mass ~ 100 GeV particles produced with cosmological density comparable to the observed dark matter density is a phenomenological disaster, but I am emphasizing that the pseudo-LSP need not be stable. There are large, otherwise attractive regions of the parameter space for low-energy supersymmetry that have been excluded on these grounds, maybe prematurely. There is a wonderful signature for this possibility: the charged pseudo-LSP, produced at LHC, though unstable on cosmological timescales, could be stable on laboratory timescales.

Let us now consider cosmology. The most distinctive features of axions as dark matter, to wit that they are produced cold, in fact so cold that they fill out a very small region of phase space and form caustics, continue to hold in the alternative axion cosmology. If anything, their derivation is cleaner, since there are no axion strings, there is a clean specification of very simple initial conditions, and in the post-inflation period, since temperatures are well below F , axions have only very feeble non-gravitational interactions.

The initial misalignment angle, which eventually materializes as the dark matter density, can provide an independent source of cosmological density perturbations, apart from ambient temperature fluctuations. If we take the inflationary origin of fluctuations at face value, we find that this additional field provides a source of isocurvature fluctuations, whose amplitude depends on the scale of inflation. Recent observations put significant constraints on the amplitude of isocurvature fluctuations, so the scale of inflation cannot be too large; but perhaps the present scenario sharpens the motivation to search for them down to low levels.

Finally, it is tempting to connect the line of thought pursued here with the other context in which anthropic reasoning has been applied to cosmology recently, that is Weinberg's discussion of the cosmological term [14]. He framed his discussion rather abstractly, without specifying a microscopic model. It is quite simple to make a model along the lines discussed here. We can go back to the comforting – but of course totally unproved! – assumption that the asymptotic value of the cosmological term, in the distant future, is zero, and that what we are observing at present is residual energy frozen into a scalar axion-like field whose value is effectively uniform over the observable Universe. This requires a small value of Λ and a large value of F , relative to the axion that plays a role in the strong P and T problems, in order that the mass $m \sim \Lambda^2/F$ should be of order the inverse Hubble time, to ensure that the field is 'stuck': $\Lambda \sim 10^{-12}$ GeV, $F \sim 10^{19}$ GeV will do the job. These values also (barely!) assure, respectively, that the vacuum energy controlled by our field can supply enough for the observed cosmological term, and that it is associated with Planck-scale physics. The closeness of this call might be considered a small bit of encouragement for observational programmes to check whether the dark energy might have become unstuck and have started to evolve in recent cosmological times.

It could appear highly unnatural, upon first sight, that symmetry-breaking at such a large scale could be associated with so little energy. It generally would be, but in axion physics it is not so unreasonable. The point is that all effects of θ -like parameters are non-perturbative, and in weak coupling they contain explicit suppression factors such as $e^{-8\pi^2/g^2}$. In QCD, that suppression is obscured, since g is not uniformly small, but it does not take much smallness in the g governing the relevant gauge theory to render this suppression factor quite small.

Having made these alterations, we can repeat our cosmological story and – within this circle of ideas – justify Weinberg's hypothesis of effectively random variation of the cosmological term and its independence from other parameters. A minor difference is that negative values of the cosmological

term do not appear. It would be logical, of course, and very interesting, to consider from an anthropic perspective the implications of allowing both the dark matter to baryon matter ratio r and the cosmological term Λ to vary independently but simultaneously. One must keep in mind that the inflated PQ horizon might be quite different from the corresponding horizon for the dark energy ‘axion’. If that occurs, then we should vary one mismatch angle over the multiverse corresponding to the smaller horizon before varying the other over the ‘multi-multiverse’ associated with the larger horizon. The most probable value may be different, since the y that maximizes $f(x, y)$ is not the same as the y that maximizes the average $\langle f(x, y) \rangle_x$ taken over x , in general. A virtue of explicit dynamical models is that they bring subtleties such as this into the foreground.

References

- [1] F. Crick. *The Astonishing Hypothesis: The Scientific Search for the Soul* (New York: Scribner, 2004).
- [2] E. Baum. *What is Thought?* (Cambridge, MA: The MIT Press, 2004).
- [3] J. Preskill, M. Wise and F. Wilczek. *Phys. Lett. B* **120** (1983), 127.
- [4] L. Abbott and P. Sikivie. *Phys. Lett. B* **120** (1983), 133.
- [5] M. Dine and W. Fischler. *Phys. Lett. B* **120** (1983), 137.
- [6] S.-Y. Pi. *Phys. Rev. Lett.* **52** (1984), 1725.
- [7] A. Linde. *Phys. Lett. B* **201** (1988), 437.
- [8] M. Turner and F. Wilczek. *Phys. Rev. Lett.* **66** (1991), 5.
- [9] M. Shifman, ed. *Handbook of QCD* (Singapore: World Scientific, 2001).
- [10] J. E. Kim. *Phys. Rep.* **150** (1987), 1.
- [11] M. Turner. *Phys. Rep.* **197** (1990) 67.
- [12] F. Wilczek. Four big questions with pretty good answers. In *Fundamental Physics – Heisenberg and Beyond*, eds. G. Buschhorn and J. Wess (Berlin: Springer 2004) [hep-ph/0201222, MIT-CTP-3236].
- [13] M. Tegmark, A. Aguirre, M. J. Rees and F. Wilczek. *Phys. Rev. D* **73** (2006), 023505 [astro-ph/0511774].
- [14] S. Weinberg. *Phys. Rev. Lett.* **59** (1987), 2067.

10

Anthropic predictions: the case of the cosmological constant

Alexander Vilenkin

Department of Physics and Astronomy, Tufts University

10.1 Introduction

The parameters we call constants of nature may, in fact, be stochastic variables taking different values in different parts of the Universe. The observed values of these parameters are then determined by chance and by anthropic selection. It has been argued, at least for some of the constants, that only a narrow range of their values is consistent with the existence of life [1–5].

These arguments have not been taken very seriously and have often been ridiculed as handwaving and unproductive. For one thing, the anthropic worldview assumes some sort of a ‘multiverse’ ensemble, consisting of multiple universes or distant regions of the same Universe, with the constants of nature varying from one member of this ensemble to another. Quantitative results cannot be obtained without a theory of the multiverse. Another criticism is that the anthropic approach does not make testable predictions; thus it is not falsifiable, and therefore not scientific.

While both of these criticisms had some force a couple of decades ago, much progress has been made since then, and the situation is now completely different. The first criticism no longer applies, because we now do have a theory of the multiverse. It is the theory of inflation. A remarkable feature of inflation is that, generically, it never ends completely. The end of inflation is a stochastic process; it occurs at different times in different parts of the Universe, and at any time there are regions which are still inflating [6, 7]. If some ‘constants’ of nature are related to dynamical fields and are allowed to vary, they are necessarily randomized by quantum fluctuations during inflation and take different values in different parts of the Universe. Thus, inflationary cosmology gives a specific realization of the multiverse ensemble and makes it essentially inevitable. (For a review, see ref. [8].)

In this chapter, I am going to address the second criticism: that anthropic arguments are unpredictive. I will try to dispel this notion and outline how anthropic models can be used to make quantitative predictions. These predictions are of a statistical nature, but they still allow models to be confirmed or falsified at a specified confidence level. I will focus on the case of the cosmological constant, whose non-zero value was predicted anthropically well before it was observed. This case is of great interest in its own right and is well suited to illustrate the issues associated with anthropic predictions.

10.2 Anthropic bounds versus anthropic predictions

For terminological clarity, it is important to distinguish between anthropic bounds and anthropic predictions. Suppose there is some parameter X , which varies from one place in the Universe to another. Suppose further that the value of X affects the chances for intelligent observers to evolve, and that the evolution of observers is possible only if X is within some interval:

$$X_{\min} < X < X_{\max}. \quad (10.1)$$

Clearly, values of X outside this interval are not going to be observed, because such values are inconsistent with the existence of observers. This statement is often called the ‘anthropic principle’.

Although anthropic bounds, like Eq. (10.1), can have considerable explanatory power, they can hardly be regarded as predictions: they are guaranteed to be right. And the ‘anthropic principle’, as stated above, hardly deserves to be called a principle; it is trivially true. This is not to say, however, that anthropic arguments cannot yield testable predictions.

Suppose we want to test a theory according to which the parameter X varies from one part of the Universe to another.¹ Then, instead of looking for the extreme values $X_{\min}$ and $X_{\max}$ that make observers impossible, we can try to predict what values of X will be measured by *typical* observers. In other words, we can make statistical predictions, assigning probabilities $P(X)$ to different values of X . ($P(X)$ is the probability that an observer randomly picked in the Universe will measure a given value of X .) If any principle needs to be invoked here, it is what I call ‘the principle of mediocrity’ [9] – the assumption that we are typical among the observers in the Universe. Quantitatively, this can be expressed as the expectation that we should find ourselves, say, within the 95% range of the distribution. This can be regarded as a prediction at a 95% confidence level. If instead we measure

¹ I assume, for simplicity, that X is variable only in space, not in time.

a value outside the expected range, this should be regarded as evidence against the theory.

10.3 The cosmological constant problem

The cosmological constant is (up to a numerical factor) the energy density of the vacuum, ρ_v . Below, I do not distinguish between the two and use the terms ‘cosmological constant’ and ‘vacuum energy density’ interchangeably. By Einstein’s mass–energy relation, the energy density is simply related to the mass density, and I will often express ρ_v in units of g cm^{-3} .

The gravitational properties of the vacuum are rather unusual: for positive ρ_v , its gravitational force is repulsive. This can be traced to the fact that, according to Einstein’s General Relativity, the force of gravity is determined not solely by the energy (mass) density ρ , but rather by the combination $(\rho + 3P)$, where P is the pressure and I put $c = 1$. In ordinary astrophysical objects, such as stars or galaxies, the pressure is much smaller than the energy density, $P \ll \rho$, and its contribution to gravity can be neglected. But, in the case of vacuum,² the pressure is equal and opposite to ρ_v ,

$$P_v = -\rho_v, \quad (10.2)$$

so that $\rho_v + 3P_v = -2\rho_v$. Pressure not only contributes significantly to the gravitational force produced by the mass, it also changes its sign.

The cosmological constant was introduced by Einstein in his 1917 paper [10], in which he applied the newly developed theory of General Relativity to the Universe as a whole. Einstein believed that the Universe was static, but to his dismay he found that the theory had no static cosmological solutions. He concluded that the theory had to be modified and he introduced the cosmological term, which amounted to endowing the vacuum with a positive energy density. The magnitude of ρ_v was chosen so that its repulsive gravity exactly balanced the attractive gravity of matter, resulting in a static world. More than a decade later, after Hubble’s discovery of the expansion of the Universe, Einstein abandoned the cosmological constant, calling it the greatest blunder of his life. But once the genie was out of the bottle, it was not so easy to put it back.

Even if we do not introduce the vacuum energy ‘by hand’, fluctuations of quantum fields, like the electromagnetic field, would still make this energy non-zero. Adding up the energies of quantum fluctuations with shorter and shorter wavelengths gives a formally infinite answer for ρ_v . The sum has

² Since the vacuum energy is proportional to the volume V it occupies, $E = \rho_v V$, the pressure is $P_v = -dE/dV = -\rho_v$.

to be cut off at the Planck length, $l_P \sim 10^{-33}$ cm, where quantum gravity effects become important and the usual concepts of space and time no longer apply. This gives a finite, but absurdly large value: $\rho_v \sim 10^{94}$ g cm $^{-3}$. A cosmological constant of this magnitude would cause the Universe to expand with a stupendous acceleration. If indeed our vacuum has energy, it should be at least 120 orders of magnitude smaller in order to be consistent with observations. In supersymmetric theories, the contributions of different fields partially cancel, and the discrepancy can be reduced to 60 orders of magnitude. This discrepancy between the expected and observed values of ρ_v is called the cosmological constant problem. It is one of the most intriguing mysteries that we are now facing in theoretical physics.

10.4 The anthropic bound

A natural resolution to the cosmological constant problem is obtained in models where ρ_v is a random variable. The idea is to introduce a dynamical dark energy component X whose energy density ρ_X varies from place to place, due to stochastic processes that occurred in the early Universe. A possible model for ρ_X is a scalar field with a very flat potential [11, 12], such that the field is driven to its minimum on an extremely long timescale, much longer than the present age of the Universe. Another possibility is a discrete set of vacuum states. Transitions between different states can then occur through nucleation and expansion of bubbles bounded by domain walls [13, 14]. The effective cosmological constant is given by $\rho_v = \rho_\Lambda + \rho_X$, where ρ_Λ is the constant vacuum energy density, which may be as large as 10^{94} g cm $^{-3}$ (with either sign). The cosmological constant problem now takes a different form: the puzzle is why we happen to live in a region where ρ_Λ is nearly cancelled by ρ_X .

The key observation, due to Weinberg [15] (see also refs. [3], [11] and [16]), is that the cosmological constant can have a dramatic effect on the formation of structure in the Universe. The observed structures – stars, galaxies and galaxy clusters – evolved from small initial inhomogeneities, which grew over eons of cosmic time by gravitationally attracting matter from surrounding regions. As the Universe expands, matter is diluted, so its density goes down as follows:

$$\rho_M = (1 + z)^3 \rho_{M0}, \quad (10.3)$$

where ρ_{M0} is the present matter density and z is the redshift.³ At the same time, the density contrast $\sigma \equiv \delta\rho/\rho$ between overdense and underdense

³ The redshift z is defined so that $(1 + z)$ is the expansion factor of the Universe between a given epoch and the present (earlier times correspond to larger redshifts).

regions keeps growing. Gravitationally bound objects form where $\sigma \sim 1$. In the Standard Model the first stars form in relatively small matter clumps of mass $\sim 10^6 M_\odot$. The clumps then merge into larger and larger objects, leading to the formation of giant galaxies like our own and galaxy clusters.

How is this picture modified in the presence of a cosmological constant? At early times, when the density of matter is high, $\rho_M \gg \rho_v$, the vacuum energy has very little effect on structure formation. But, as the Universe expands and the matter density decreases, the vacuum density ρ_v remains constant and eventually becomes greater than ρ_M . At this point, the character of cosmic expansion changes. Prior to vacuum-domination, the expansion is slowed down by gravity, but afterwards it begins to accelerate, due to the repulsive gravity of the vacuum. Weinberg showed that the growth of density inhomogeneities effectively stops at that epoch. If no structures were formed at earlier times, then none will *ever* be formed.

It seems reasonable to assume that the existence of stars is a necessary prerequisite for the evolution of observers. We also need to require that the stars belong to sufficiently large bound objects – galaxies – so that their gravity is strong enough to retain the heavy elements dispersed in supernova explosions. These elements are necessary for the formation of planets and observers. An anthropic bound on the vacuum energy can then be obtained by requiring that ρ_v does not dominate before the redshift $z_{\max}$ when the earliest galaxies are formed. With the aid of Eq. (10.3), this yields

$$\rho_v \leq (1 + z_{\max})^3 \rho_{M0}. \quad (10.4)$$

The most distant galaxies observed at the time when Weinberg wrote his paper had redshifts $z \sim 4.5$. Assuming that $z_{\max} \sim 4.5$, Eq. (10.4) yields the bound $\rho_v \leq 170 \rho_{M0}$. A more careful analysis by Weinberg showed that in order to prevent structure formation, ρ_v needs to be three times greater than suggested by Eq. (10.4), so a more accurate bound is given by

$$\rho_v \leq 500 \rho_{M0} \quad (10.5)$$

(see ref. [15]). Of course, the observation of galaxies at $z \sim 4.5$ means only that $z_{\max} \geq 4.5$, and Weinberg referred to Eq. (10.5) as ‘a lower bound on the anthropic upper bound on ρ_v ’. At present, galaxies are observed at considerably higher redshifts, up to $z \sim 10$. The corresponding bound on ρ_v would be

$$\rho_v \leq 4000 \rho_{M0}. \quad (10.6)$$

For negative values of ρ_v , the vacuum gravity is attractive, and vacuum-domination leads to a rapid recollapse of the Universe. An anthropic lower

bound on ρ_v can be obtained in this case by requiring that the Universe does not recollapse before life had a chance to develop [3,17]. Assuming that the timescale for life evolution is comparable to the present cosmic time, one finds⁴ $\rho_v \geq -\rho_{M0}$.

The anthropic bounds are narrower, by many orders of magnitude, than the particle physics estimates for ρ_v . Moreover, as Weinberg noted, there is a prediction implicit in these bounds. He wrote [18]:

... if it is the anthropic principle that accounts for the smallness of the cosmological constant, then we would expect a vacuum energy density $\rho_v \sim (10 - 100)\rho_{M0}$, because there is no anthropic reason for it to be any smaller.

One has to admit, however, that the anthropic bounds fall short of the observational bound, $(\rho_v)_{\text{obs}} \leq 4\rho_{M0}$, by a few orders of magnitude. If all the values in the anthropically allowed range were equally probable, an additional fine-tuning by a factor of 100–1000 would still be needed.

10.5 Anthropic predictions

The anthropic bound given by Eq. (10.4) specifies the value of ρ_v which makes galaxy formation barely possible. However, if ρ_v varies in space, then most of the galaxies will not be in regions characterized by these marginal values, but rather in regions where ρ_v dominates after a substantial fraction of matter had already clustered into galaxies.

To make this quantitative, we define the probability distribution $\mathcal{P}(\rho_v)d\rho_v$ as being proportional to the number of observers in the Universe who will measure ρ_v in the interval $d\rho_v$. This distribution can be represented as a product [9]:

$$\mathcal{P}(\rho_v)d\rho_v = n_{\text{obs}}(\rho_v)\mathcal{P}_{\text{prior}}(\rho_v)d\rho_v. \quad (10.7)$$

Here, $\mathcal{P}_{\text{prior}}(\rho_v)d\rho_v$ is the prior distribution, which is proportional to the volume of those parts of the Universe where ρ_v takes values in the interval $d\rho_v$, and $n_{\text{obs}}(\rho_v)$ is the number of observers that are going to evolve per unit volume. The distribution given by Eq. (10.7) gives the probability that a randomly selected observer is located in a region where the effective cosmological constant is in the interval $d\rho_v$.

Of course, we have no idea how to calculate n_{obs} , but what comes to the rescue is the fact that the value of ρ_v does not directly affect the physics and chemistry of life. As a rough approximation, we can then assume that

⁴ An important distinction between positive and negative values of ρ_v is that, for $\rho_v > 0$, galaxies that formed prior to vacuum-domination can survive indefinitely in the vacuum-dominated Universe.

$n_{\text{obs}}(\rho_v)$ is simply proportional to the fraction of matter f clustered in giant galaxies like ours (with mass $M \geq M_G = 10^{12} M_\odot$),

$$n_{\text{obs}}(\rho_v) \propto f(M_G, \rho_v). \quad (10.8)$$

The idea is that there is a certain number of stars per unit mass in a galaxy and a certain number of observers per star. The choice of the galactic mass M_G is an important issue; I will comment on it in Section 10.6.

The calculation of the prior distribution $\mathcal{P}_{\text{prior}}(\rho_v)$ requires a particle physics model which allows ρ_v to vary and a multiverse model that would generate an ensemble of sub-universes with different values of ρ_v . An example of a suitable particle theory is superstring theory, which appears to admit an incredibly large number of vacua (possibly as large as 10^{1000} [19–21]), characterized by different values of particle masses, couplings and other parameters, including the cosmological constant. When this is combined with the cosmic inflation scenario, one finds that bubbles of different vacua copiously nucleate and expand during inflation, producing exponentially large regions with all possible values of ρ_v . Given a particle physics model and a model of inflation, one can in principle calculate $\mathcal{P}_{\text{prior}}(\rho_v)$. Examples of calculations for specific models have been given in refs. [12], [22] and [23].⁵ Needless to say, the details of the fundamental theory and the inflationary dynamics are too uncertain for a definitive calculation of $\mathcal{P}_{\text{prior}}$. We shall instead rely on the following general argument [28, 29].

Suppose some parameter X varies in the range ΔX and is characterized by a prior distribution $\mathcal{P}_{\text{prior}}(X)$. Suppose further that X affects the number of observers in such a way that this number is non-negligible only in a very narrow range $\Delta X_{\text{obs}} \ll \Delta X$. Then one can expect that the function $\mathcal{P}_{\text{prior}}(X)$ with a large characteristic range of variation should be very nearly constant in the tiny interval ΔX_{obs} .⁶ In the case of ρ_v , the range $\Delta \rho_v$ is set by the Planck scale or by the supersymmetry-breaking scale, and we have $(\Delta \rho_v)_{\text{obs}} / \Delta \rho_v \sim 10^{-60} - 10^{-120}$. Hence, we expect

$$\mathcal{P}_{\text{prior}}(\rho_v) \approx \text{const.} \quad (10.9)$$

⁵ There are still some open issues regarding the definition of $\mathcal{P}_{\text{prior}}$ for models with a discrete spectrum of variable ‘constants’ [24–26]. For a recent discussion and a proposed resolution, see ref. [27].

⁶ A very different model for the prior distribution was considered by Rubakov and Shaposhnikov [30]. They assumed that $\mathcal{P}_{\text{prior}}(X)$ is a sharply peaked function with a peak outside the anthropic range $\mathcal{A}$ and argued that the observed value of X should then be very close to the boundary of $\mathcal{A}$. We note that, in this case, the peak of the full distribution is likely to be in a life-hostile environment, where both $\mathcal{P}_{\text{prior}}(X)$ and $n_{\text{obs}}(X)$ are very small. In the case of the cosmological constant, this would mean that the number density of galaxies is very low. This is not the case in our observable region, indicating that the model of ref. [30] does not apply.

I emphasize that the assumption here is that the value $\rho_v = 0$ is not in any way special, as far as the fundamental theory is concerned, and is, therefore, not a singular point of $\mathcal{P}_{\text{prior}}(\rho_v)$.

Combining Eqs. (10.7) to (10.9), we obtain

$$\mathcal{P}(\rho_v) \propto f(M_G, \rho_v). \quad (10.10)$$

In ref. [9], where I first introduced the anthropic probability distributions of the form given by Eq. (10.7), I did not attempt a detailed calculation of the distribution for ρ_v , resorting instead to a rough estimate. If we denote by z_G the redshift at the epoch of galaxy formation, then most of the galaxies should be in regions where the vacuum energy dominates only after some redshift $z_v \leq z_G$. Regions with $z_v \gg z_G$ will have very few galaxies, while regions with $z_v \ll z_G$ will be rare, simply because they correspond to a very narrow range of ρ_v near zero. Hence, we expect a typical galaxy to be located in a region where

$$z_v \sim z_G. \quad (10.11)$$

The expected value of ρ_v is then given by

$$\rho_v \sim (1 + z_G)^3 \rho_{M0}. \quad (10.12)$$

The choice of the galaxy formation epoch z_G is related to the choice of the galactic mass M_G in Eq. (10.8). I used $z_G \sim 1$, obtaining $\rho_v \sim 8\rho_{M0}$.

A similar approach was later developed by Efstathiou [31]. The main difference is that he calculated the fraction of clustered matter f at the time corresponding to the observed value of the microwave background temperature, $T_0 = 2.73$ K, while my suggestion was to use the asymptotic value of f as $t \rightarrow \infty$. The two approaches correspond to different choices of the reference class of observers, among whom we expect to be typical. Efstathiou's choice includes (roughly) only observers that have evolved until the present, while my choice includes all observers – present, past and future. If we are truly typical, and live at the time when most observers live, the two methods should give similar results. Indeed, one finds that the probability distributions calculated by these methods are nearly identical.⁷

10.6 Comparison with observations

Despite a number of observational hints that the cosmological constant might be non-zero (see, for example, ref. [32]), its discovery still came as a

⁷ L. Pogosian (private communication). The original calculation by Efstathiou gave a different result, but that calculation contained an error, which was later pointed out by Weinberg [29].

great surprise to most physicists and astronomers. Observations of distant supernovae by two independent groups in 1997–98 provided strong evidence that the expansion of the Universe is accelerating [33]–[35]. The simplest interpretation of the data was in terms of a cosmological constant with $\rho_v \sim 2.3\rho_{M0}$. Further evidence came from the cosmic microwave background and galaxy clustering observations, and by now the case for the cosmological constant is very strong.

The discovery of the cosmological constant was particularly shocking to particle physicists, who almost universally believed that it should be zero. They assumed that something so small could only be zero and searched for a new symmetry principle or a dynamical adjustment mechanism that would force ρ_v to vanish. The observed value of ρ_v brought yet another puzzle. The matter density ρ_M and the vacuum energy density ρ_v scale very differently with the expansion of the Universe. In the early Universe the matter density dominates, while in the asymptotic future it becomes negligible. There is only one epoch in the history of the Universe when $\rho_M \sim \rho_v$. It is difficult to understand why we happen to live in this very special epoch. This is the so-called cosmic coincidence problem.

The coincidence is easily understood in the framework of the anthropic approach [36,37]. The galaxy formation epoch, $z_G \sim 1-3$, is close to the present cosmic time, and the anthropic model predicts that vacuum-domination should begin at $z \sim z_G$ from Eq. (10.11). This explains the coincidence.

The probability distribution for ρ_v based on Eq. (10.10) was extensively analyzed in ref. [38]. The distribution depends on the amplitude of galactic-scale density perturbations, σ , which can be specified at some suitably selected epoch (for example, the epoch of recombination). Until recently, significant uncertainties in this quantity complicated the comparison of anthropic predictions with the data [23,38]. These uncertainties appear now to have been mostly resolved [39]. In Fig. 10.1 we plot, following ref. [40], the resulting probability distribution per logarithmic interval of ρ_v . Only positive values of ρ_v are considered, so this can be regarded as a conditional distribution, given that $\rho_v > 0$. On the horizontal axis, ρ_v is plotted in units of the observed vacuum energy density, $\rho_v^* = 7 \times 10^{-30} \text{ g cm}^{-3}$. The ranges of the distribution excluded at the 68% and 95% confidence levels are indicated by light and dark shading, respectively.

We note that the confidence level ranges in Fig. 10.1 are rather broad. This corresponds to a genuine large variance in the cosmic distribution of ρ_v . The median value of the distribution is about twenty times greater than the observed value. But still, the observed value ρ_v^* falls well within the range of anthropic prediction at the 95% confidence level.

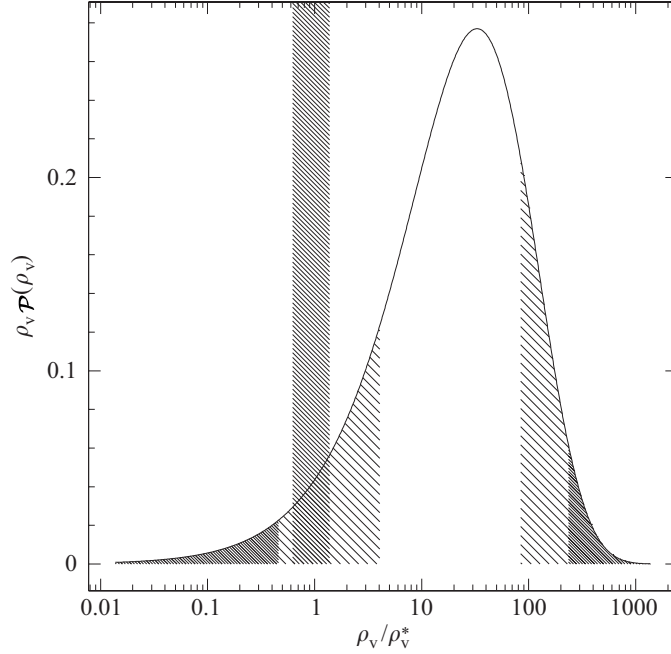


Fig. 10.1. The probability density per logarithmic interval of ρ_v . The lightly and densely shaded areas are the regions excluded at 68% and 95% levels, respectively. The uncertainty in the observed value ρ_v^* is indicated by the vertical strip.

At this point, I would like to comment on some important assumptions that went into the successful prediction of the observed value of ρ_v . First, we assumed the flat prior probability distribution given by Eq. (10.9). Analysis of specific models shows that this assumption is indeed valid in a wide class of cases, but it is not as automatic as one might expect [12, 22, 41, 42]. In particular, it is not clear that it is applicable to superstring-inspired models of the type discussed in refs. [19]–[21]. (We discuss this further in Section 10.8.)

Second, we used the value of $M_G = 10^{12} M_\odot$ for the galactic mass in Eq. (10.10). This amounts to assuming that most observers live in giant galaxies like the Milky Way. We know from observations that some galaxies existed already at $z = 10$, and the theory predicts that some dwarf galaxies and dense central parts of giant galaxies could form as early as $z = 20$. If observers were as likely to evolve in galaxies that formed early as in those that formed late, the value of ρ_v indicated by Eq. (10.12) would be far greater than observed. Clearly, the agreement is much better if we assume that the conditions for civilizations to emerge arise mainly in galaxies which form at lower redshifts, $z_G \sim 1$.

Following ref. [42], I will now point to some directions along which the choice of $z_G \sim 1$ may be justified. As already mentioned, one problem with dwarf galaxies is that their mass may be too small to retain the heavy elements dispersed in supernova explosions. Numerical simulations suggest that the fraction of heavy elements retained is $\sim 30\%$ for a $10^9 M_\odot$ galaxy and is negligible for much smaller galaxies [43]. Hence, we have to require that the structure formation hierarchy evolves up to mass scales $\sim 10^9 M_\odot$ or higher prior to the vacuum energy dominating. This gives the condition $z_G \leq 3$, but falls short of explaining $z_G \sim 1$.

Another point to note is that smaller galaxies, formed at earlier times, have a higher density of matter. This may increase the danger of nearby supernova explosions and the rate of near encounters with stars, large molecular clouds or dark matter clumps. Gravitational perturbations of planetary systems in such encounters could send a rain of comets from the Oort-type clouds towards the inner planets, causing mass extinctions.

Our own galaxy has definitely passed the test for the evolution of observers, and the principle of mediocrity suggests that most observers may live in galaxies of this type. The Milky Way is a giant spiral galaxy. The dense central parts of such galaxies were formed at a high redshift, $z \geq 5$, but their discs were assembled at $z \leq 1$ [44]. Our Sun is located in the disc, and if this situation is typical, then the relevant epoch to use in Eq. (10.12) is the redshift $z_G \sim 1$ associated with the formation of the discs of giant galaxies.⁸

It should be clear from this discussion that the confidence ranges in Fig. 10.1 are not to be taken too literally. The distribution in Fig. 10.1 is based on Eq. (10.8), which is only a very rough model for the density of observers. It assumes that all galaxies of mass $M > M_G$, regardless of when they are formed, will have the same average number of observers per unit mass. This probably overestimates the density of observers at high values of ρ_v , corresponding to denser galaxies which are more hazardous for life. More accurate models for $n_{\text{obs}}(\rho_v)$ will require a better understanding of galactic evolution and the conditions necessary to sustain habitable planetary systems.

10.7 Predictions for the equation of state

A generic prediction of anthropic models for the vacuum energy is that the vacuum equation of state given by Eq. (10.2) should hold with very high accuracy [42]. In models of discrete vacua, this equation of state is

⁸ These remarks may or may not be on the right track, but if the observed value of ρ_v is due to anthropic selection, then, for one reason or another, the evolution of intelligent life should require conditions which are found mainly in giant galaxies, which completed their formation at $z_G \sim 1$. This is a prediction of the anthropic approach.

guaranteed by the fact that in each vacuum the energy density is a constant and can only change by nucleation of bubbles. If ρ_X is a scalar field potential, it must satisfy the slow-roll condition, i.e. the field should change slowly on the timescale of the present age of the Universe. The slow-roll condition is likely to be satisfied by many orders of magnitude. Although it is possible to adjust the potential so that it is only marginally satisfied, it is satisfied by a very wide margin in generic models. This implies the equation of state given by Eq. (10.2).

There is also a related prediction, which is not likely to be tested anytime soon. In anthropic models, ρ_v can take both positive and negative values, so the observed positive dark energy will eventually start decreasing and turn negative, and our part of the Universe will recollapse to a big crunch. Since the evolution of ρ_v is expected to be very slow on the present Hubble scale, we do not expect this to happen sooner than a trillion years from now [42].

It should be noted that the situation may be different in more complicated models, involving more than one scalar field. It has been shown in ref. [23] that the equation of state in such models may significantly deviate from Eq. (10.2), and the recollapse may occur on a timescale comparable to the lifetime of the Sun. Observational tests distinguishing between the two types of models have been discussed in refs. [45]–[47]. Recent observations [39] yield $P_v/\rho_v = -1 \pm 0.1$, consistent with the simplest models.

10.8 Implications for particle physics

Anthropic models for the cosmological constant have non-trivial implications for particle physics. Scalar field models require the existence of fields with extremely flat potentials. Models with a discrete set of vacua require that the spectrum of values of ρ_v should be very dense, so that there are many such values in the small anthropically allowed range. This points to the existence of very small parameters that are absent in familiar particle physics models. Some ideas on how such small parameters could arise have been suggested in refs. [12], [41] and [48]–[51].

A different possibility, which has now attracted much attention, is inspired by superstring theory. This theory presumably has an enormous number of different vacua, scattered over a vast ‘string theory landscape’. The spectrum of ρ_v (and of other particle physics constants) can then be very dense without any small parameters, due to the sheer number of vacua [19–21]. This picture, however, entails a potential problem. Vacua with close values of ρ_v are not expected to be close to one another in the ‘landscape’, and there seems to be no reason to expect that they will be chosen with equal

probability by the inflationary dynamics. Hence, we can no longer argue that the prior probability distribution is flat. In fact, since inflation is characterized by an exponential expansion of the Universe, and the expansion rate is different in different parts of the landscape, the probabilities for well separated vacua are likely to differ by large exponential factors. If indeed the prior distribution is very different from flat, this may destroy the successful anthropic prediction for ρ_v . This issue requires further study, and I am sure we are going to hear more about it.

10.9 Including other variables

If the cosmological constant is variable, then it is natural to expect that some other ‘constants’ could vary as well, and it has been argued that including other variables may drastically modify the anthropic prediction for ρ_v [4, 52, 53]. The idea is that the adverse effect on the evolution of observers due to a change in one variable may be compensated by an appropriate change in another variable. As a result, the peak of the distribution may drift into a totally different area of the parameter space. While this is a legitimate concern, specific models with more than one variable that have been analyzed so far suggest that the anthropic prediction for ρ_v is rather robust.

Suppose, for example, that ρ_v and the primordial density contrast σ (specified at recombination) are both allowed to vary. Then we are interested in the joint distribution

$$\mathcal{P}(\rho_v, \sigma) d\rho_v d\sigma. \quad (10.13)$$

Using the same assumptions⁹ as in Section 10.6 and introducing a new variable $y = \rho_v/\sigma^3$, one finds [42] that this distribution factorizes to the following form:¹⁰

$$\sigma^3 \mathcal{P}_{\text{prior}}(\sigma) d\sigma \cdot f(y) dy, \quad (10.14)$$

⁹ The assumption that the number of observers is simply proportional to the fraction of matter clustered into galaxies may not give a good approximation in regions where σ is very large. In such regions, galaxies form early and are very dense, so the chances for life to evolve may be reduced. A more accurate calculation should await better estimates for the density of habitable stellar systems.

¹⁰ Note that there is no reason to expect the prior distribution for σ to be flat. The amplitude of density perturbations is related to the dynamics of the inflaton field that drives inflation and is therefore strongly correlated with the amount of inflationary expansion. Hence, we expect $\mathcal{P}_{\text{prior}}$ to be a non-trivial function of σ . In fact, it follows from Eq. (10.14) that $\mathcal{P}_{\text{prior}}(\sigma)$ should decay at least as fast as σ^{-3} in order for the distribution to be integrable [36].

where $f(y)$ is the fraction of matter clustered in galaxies (which depends only on the combination ρ_v/σ^3).

After integration over σ , we obtain essentially the same distribution as before, but for a new variable y . The prediction now is not for a particular value of ρ_v , but for a relation between ρ_v and σ . Comparison of the predicted and observed values of y is given by the same graph as in Fig. 10.1, with a suitable rescaling of the horizontal axis. As before, the 95% confidence level prediction is in agreement with the data.

Another example is a model where the neutrino masses are assumed to be anthropic variables. Neutrinos are elusive light particles, which interact very weakly and whose masses are not precisely known. The current astrophysical upper bound on the neutrino mass is $m_\nu \leq 0.5$ eV [39] and the lower bound from the neutrino oscillation data is $m_\nu \geq 0.05$ eV [54]. (In what follows, m_ν denotes the sum of the three neutrino masses.) It has been suggested in ref. [55] that small values of the neutrino masses may be due to anthropic selection. A small increase of m_ν can have a large effect on galaxy formation. Neutrinos stream out of overdense regions, slowing the growth of density perturbations. The fraction of mass that neutrinos contribute to the total density of the Universe is proportional to m_ν . Thus, perturbations will grow slower, and there will be fewer galaxies, in regions with larger values of m_ν . A calculation along the same lines as in Section 10.5 yields a prediction $0.07 \text{ eV} < m_\nu < 5.7 \text{ eV}$ at the 95% confidence level.

In ref. [40] this model was extended, allowing both m_ν and ρ_v to be anthropic variables. The resulting probability distribution $\mathcal{P}(\rho_v, m_\nu)$ is concentrated in a localized region of the parameter space. Its peak is not far from the peaks of the individual distributions for ρ_v and m_ν . In fact, inclusion of m_ν somewhat improves the agreement of the prediction for ρ_v with the data.

The parameters ρ_v , σ and m_ν share the property that they do not directly affect life processes. Other parameters of this sort include the mass of dark matter particles and the number of baryons per photon. The effects of varying these parameters have been discussed in refs. [4] and [52]. In particular, Aguirre [52] argued that values of the baryon-to-photon ratio much higher than observed may be anthropically favoured. What he showed, in fact, is that this proposition cannot at present be excluded. This is an interesting issue and certainly deserves further study. Extensions to parameters such as the electron mass or charge, which do affect life processes, are on much shakier ground. Until these processes are much better understood, we will have to resort to qualitative arguments, as in refs. [1]–[3] and [5].

10.10 Concluding remarks

The case of the cosmological constant demonstrates that anthropic models can be subjected to observational tests and can be confirmed or ruled out at a specified confidence level. It also illustrates the limitations and difficulties of anthropic predictions.

The situation we are accustomed to in physics is that the agreement between theory and observations steadily improves, as the theoretical calculations are refined and the accuracy of measurements increases. This does not apply in anthropic models. Here, predictions are in the form of probability distributions, having an intrinsic variance which cannot be further reduced.

However, there is ample possibility for anthropic models to be falsified. This could have happened in the case of the cosmological constant if the observed value turned out to be much smaller than it actually is. And this may still happen in the future, with improved understanding of the prior and anthropic factors in the distribution given by Eq. (10.7). Also, there is always a possibility that a compelling non-anthropropic explanation for the observed value of ρ_v will be discovered. As of today, no such explanation has been found, and the anthropic model for ρ_v can certainly be regarded a success. This may be the first evidence that we have for the existence of a vast multiverse beyond our horizon.

Acknowledgements

I am grateful to Jaume Garriga and Ken Olum for comments and to Levon Pogosian for his help with numerical calculations and Fig. 10.1. This work was supported in part by the National Science Foundation.

References

- [1] B. Carter. In *Confrontation of Cosmological Theories with Observational Data*, ed. M. Longair (Dordrecht: Reidel, 1974), p. 291.
- [2] B. J. Carr and M. J. Rees. *Nature* **278** (1979), 605.
- [3] J. D. Barrow and F. J. Tipler. *The Anthropic Cosmological Principle* (Oxford: Clarendon, 1986).
- [4] M. Tegmark and M. J. Rees. *Astrophys. J.* **499** (1998), 526.
- [5] C. J. Hogan. *Rev. Mod. Phys.* **72** (2000), 1149.
- [6] A. Vilenkin. *Phys. Rev. D* **27** (1983), 2848.
- [7] A. D. Linde. *Phys. Lett. B* **175** (1986), 395.
- [8] A. D. Linde. *Particle Physics and Inflationary Cosmology* (Chur, Switzerland: Harwood Academic, 1990).
- [9] A. Vilenkin. *Phys. Rev. Lett.* **74** (1995), 846.
- [10] A. Einstein. *Sitz. Ber. Preuss. Akad. Wiss.* **142** (1917).

- [11] A. D. Linde. In *300 Years of Gravitation*, eds. S. W. Hawking and W. Israel (Cambridge: Cambridge University Press, 1987).
- [12] J. Garriga and A. Vilenkin. *Phys. Rev. D* **61** (2000), 083502.
- [13] J. D. Brown and C. Teitelboim. *Nucl. Phys. B* **279** (1987), 787.
- [14] L. Abbott. *Phys. Lett. B* **195** (1987), 177.
- [15] S. Weinberg. *Phys. Rev. Lett.* **59** (1987), 2607.
- [16] P. C. W. Davies and S. Unwin. *Proc. Roy. Soc.* **377** (1981), 147.
- [17] R. Kallosh and A. D. Linde. *Phys. Rev. D* **67** (2003), 023510.
- [18] S. Weinberg. *Rev. Mod. Phys.* **61** (1989), 1.
- [19] R. Bousso and J. Polchinski. *JHEP* **0006** (2000), 006.
- [20] M. R. Douglas. *JHEP* **0305**, (2003), 046.
- [21] L. Susskind. This volume (2007) [hep-th/0302219].
- [22] J. Garriga and A. Vilenkin. *Phys. Rev. D* **64** (2001), 023517.
- [23] J. Garriga, A. D. Linde and A. Vilenkin. *Phys. Rev. D* **61** (2004), 063521.
- [24] A. D. Linde, D. A. Linde and A. Mezhlumian. *Phys. Rev. D* **49** (1994) 1783.
- [25] J. Garcia-Bellido and A. D. Linde. *Phys. Rev. D* **51** (1995), 429.
- [26] J. Garriga and A. Vilenkin. *Phys. Rev. D* **64** (2001), 023507.
- [27] J. Garriga, D. Schwartz-Perlov, A. Vilenkin and S. Winitzki. *J. Cosmol. Astropart. Phys.*, **0601** (2006), 017.
- [28] A. Vilenkin. In *Cosmological Constant and the Evolution of the Universe*, eds. K. Sato *et al.* (Tokyo: Universal Academy Press, 1996).
- [29] S. Weinberg. In *Critical Dialogues in Cosmology*, ed. N. G. Turok (Singapore: World Scientific, 1997).
- [30] V. A. Rubakov and M. E. Shaposhnikov. *Mod. Phys. Lett. A* **4** (1989), 107.
- [31] G. Efstathiou. *Mon. Not. Roy. Astron. Soc.* **274** (1995), L73.
- [32] M. Fukugita. In *Critical Dialogues in Cosmology*, ed. N. G. Turok (Singapore: World Scientific, 1997)
- [33] S. Perlmutter, S. Gabi, G. Goldhaber *et al.* *Astrophys. J.* **483** (1997), 565.
- [34] B. P. Schmidt, N. B. Suntzeff, M. M. Phillips *et al.* *Astrophys. J.* **507** (1998), 46.
- [35] A. G. Riess, A. V. Filippenko, P. Challis *et al.* *Astron. J.* **116** (1998), 1009.
- [36] J. Garriga, M. Livio and A. Vilenkin. *Phys. Rev. D* **61** (2000), 023503.
- [37] S. Bludman. *Nucl. Phys. A* **663** (2000), 865.
- [38] H. Martel, P. R. Shapiro and S. Weinberg. *Astrophys. J.* **492** (1998), 29.
- [39] M. Tegmark, M. A. Strauss, M. R. Blanton *et al.* *Phys. Rev. D* **69** (2004), 103501.
- [40] L. Pogosian, M. Tegmark and A. Vilenkin. *J. Cosmol. Astropart. Phys.*, **0407** (2004), 005.
- [41] S. Weinberg. *Phys. Rev. D* **61** 103505 (2000) [astro-ph/0005265].
- [42] J. Garriga and A. Vilenkin. *Phys. Rev. D* **67** (2003), 043503.
- [43] M. MacLow and A. Ferrara. *Astrophys. J.* **513** (1999), 142.
- [44] R. G. Abraham and S. van der Bergh. *Science*, **293** (2001), 1273.
- [45] S. Dimopoulos and S. Thomas. *Phys. Lett. B* **573** (2003), 13.
- [46] R. Kallosh, J. Kratochvil, A. Linde, E. Linder and M. Shmakova. *J. Cosmol. Astropart. Phys.*, **0310** (2003), 015.
- [47] J. Garriga, L. Pogosian and T. Vachaspati. *Phys. Rev. D* **69** (2004), 063511.
- [48] J. L. Feng, J. March-Russell, S. Sethi and F. Wilczek. *Nucl. Phys. B* **602** (2001), 307.
- [49] T. Banks, M. Dine and L. Motl. *JHEP*, **0101** (2001), 031.

- [50] J. Donoghue. *JHEP*, **0008** (2000), 022.
- [51] G. Dvali and A. Vilenkin. *Phys. Rev. D* **64** (2001), 063509.
- [52] A. Aguirre. *Phys. Rev. D* **64** (2001), 083508.
- [53] T. Banks, M. Dine and E. Gorbatov. *JHEP*, **0408** (2004), 058.
- [54] J. N. Bahcall. *JHEP*, **0311** (2003), 004.
- [55] M. Tegmark, L. Pogosian and A. Vilenkin. *Phys. Rev. D* **71** (2005), 103523.

11

The definition and classification of universes

James D. Bjorken

Stanford Linear Accelerator Center, Stanford University

11.1 Introduction

When discussing the concept of multiple universes, it is a major challenge to keep the discourse within the bounds of science. There is an acute need to define what is being talked about. The issues include the following questions. How does one in general define a universe? Should one entertain different laws of physics in different universes? What are the most important parameters and/or features that characterize a universe? Once a parametrization has been attained, what is the differential probability of finding a universe with specified parameters? Is the integral of this distribution function finite or infinite?

A useful and familiar analogy is to consider planet Earth as a universe. It is, after all, not so long ago that this was mankind's paradigm. Then one may take the ensemble of universes, or multiverse, to be the set of all compact massive objects within the solar system which orbit the Sun and/or each other. Alternatively, one may take as a toy multiverse the set of all planets in the Galaxy or our universe. In either case, it is clear that the characterization of individual members of the ensemble is a very difficult task and requires a sophisticated understanding of much of planetary science, especially the experimental side of the subject.

One simplification of the general problem of classification is to restrict the consideration to that subset of universes (or – in the analogy – planets) which are nearly the same as our own. And this restriction can be naturally expressed in anthropic terms, by asking that the subset in question be that which admits in principle the existence of life as we know it. Even so, in the case of planets, this restricted problem is still very difficult. It is not clear whether our universe contains a large set of such planets, or whether

the set only consists of our own planet. The problem is nicely described in the book *Rare Earth* by Brownlee and Ward [1].

If the problem of characterizing habitable universes within the multiverse is as complex as that of characterizing habitable planets within our universe, it is not at all clear that scientific methods will ever lead to noticeable progress in understanding. We can only hope that the case of universes is simpler than that of planets. In what follows, we will assume that the characterization of universes can be made concise, and we will shape our further working assumptions with this in mind.

11.2 What is a universe?

The characterization of universes naturally begins with the characterization of our own. In what follows, we shall adopt uncritically the Standard Model of contemporary cosmology. We assume that the spacetime geometry within each universe, as defined below in more detail, is spatially flat and can be described (in the large) by the Friedmann–Robertson–Walker (FRW) metric throughout its history. We assume that there is a non-vanishing cosmological constant, with dark energy comprising at present 70% of the energy of the universe, with most of the remainder contributed by dark matter. We also assume that prior to the ignition of the (radiation-dominated) big bang, there was an inflationary epoch characterized by a quasi-de Sitter spacetime, during which the FRW scale factor inflated by at least thirty powers of ten.

Strictly speaking, the size of such a universe is infinite, because the FRW spatial volume is infinite. But even if the FRW metric can be extrapolated to arbitrarily large distances, it still remains the case that almost all of this spacetime region is causally disconnected from us and will remain so to our descendants – provided the cosmological constant remains non-vanishing in the future (something which we will assume, for better or worse). So we place a box with comoving walls, centred on us, into the FRW spacetime. The dimension of the box at the present time is taken to be of order ten times the nominal size of our universe, which is 30 000 Mpc or 10^{29} cm. For practical purposes, we assume periodic boundary conditions at the surface of the box. Sensitivity of physical phenomena to this artifice can be tested by varying the (comoving) dimensions of the box. We do not expect significant sensitivity, because the box surface will be causally disconnected from us and our descendants.

Just as we bound by hand the spatial extent of our universe, we shall also bound the temporal extent. We choose as the initial time a value for which the physical size of the comoving box is not too much larger than the Planck

scale. Clearly, if the initial time were to be chosen much smaller, the size of the box would become small in comparison to the Planck scale, and the uncertainties in the underlying physics would grow considerably. And again there is good reason to believe that the phenomenology accessible to us is not strongly dependent upon details of the assumed initial state – although this question is still under vigorous debate.

It is also tempting to put a bound on the future as well as the past. Assuming the cosmological constant to be truly constant, there will be in the future a landmark time, at about 10^{12} y, when the temperature of the primordial black-body radiation decreases to the Hawking temperature of our de Sitter spacetime and almost all of the matter entropy has disappeared behind the de Sitter horizon. This occurs after the universe has inflated by a factor of about 10^{30} more than at present. Beyond this time the universe within the de Sitter horizon (the part causally connected to us and our descendants) is a truly quantum system. Again the uncertainties in the theoretical description are sure to be much higher, so we draw the line at this point.

In summary, we define our universe as the region of spacetime within the spacetime box defined above. Theoretical physics restricted to ‘inside the box’ has a chance of being within the realm of physical science, i.e. verifiable or falsifiable by conceivable experiments. Outside the box it is much less likely that this is the case. I prefer to stay inside the box and, at most, compare the physics in our box with that in other hypothetical boxes, similarly constructed, located elsewhere in spacetime.

The most gross features of the universe ‘inside the box’ can be best seen in the limit of ignoring small details, such as the difference between the GUT and Planck scales, the difference between the ‘reheat’ temperature and the Planck scale, and the very existence of ordinary and dark matter. Each of these simplifications involves replacing factors of 10^5 or so by factors of order unity. While this is extreme, it is not a big deal in comparison with the remaining factor of 10^{30} in the description, which is ubiquitous. The history of this ‘universe in a box for dummies’ divides itself into three epochs: quasi-de Sitter inflation, radiation-dominated big bang and dark-energy-dominated de Sitter expansion. Each epoch is characterized by an increase in the FRW scale factor of about 10^{30} . After the first epoch, the entropy of the radiation quanta accessible to our observation, and that of our progeny (of order 10^{90}), is enclosed in a volume with dimensions of millimetres, a scale of order 10^{30} times larger than the Planck scale. And after the second epoch (roughly now), the temperature of the primordial radiation is 10^{30} larger than the Hawking temperature of the future de Sitter

spacetime and a factor 10^{30} smaller than the Planck temperature. All these factors of 10^{30} can be traced to the ratio of the dark-energy scale to the Planck-energy scale, i.e. to the value of the cosmological constant.

From this viewpoint, the cosmological constant is the most robust parameter characterizing the spacetime architecture of our universe and the sub-ensemble of universes which have properties similar to ours. Indeed, we will define the size of a universe in these terms: it is the value of the inverse Hubble constant in the future, when dark energy overwhelms matter in the FRW evolution.

11.3 Standard model and cosmological parameters in the multiverse

When considering the multiverse at large, it is possible that different universes have different gross histories. Do other universes go through inflation and radiation-dominated big bangs? We shall assume that there is a subset which does so, in a manner similar to our own universe, and limit our attention to that subset. It is also possible that different universes have different laws of physics. For example, the pattern of symmetries in other universes may not be the same as what is expressed by the Standard Model group; even the degrees of freedom might differ. Again, we do not here entertain such possibilities, but restrict our attention to those universes which have the same Standard Model effective action as our own. However, we shall allow the parameters in that effective action to differ in different universes.

The candidate parameters which are necessary (but quite probably not sufficient) to specify a universe fall into different classes. One class of Standard Model parameters consists of those relevant to vacuum structure. This includes the scale of the dark energy ($\mu = 2$ meV), the QCD condensate ($\Lambda_{\text{QCD}} = 200$ MeV), the electroweak vacuum condensate ($v = 250$ GeV) and perhaps the grand unification (GUT) scales, ranging from 10^{13} GeV (neutrino condensates?) to 10^{16} GeV (coupling constant unification). Another parameter set consists of the magnitudes of the dimensionless coupling constants characterizing the strengths of the Standard Model forces. Another distinct set is the large number of parameters characterizing the masses and mixings of quarks and leptons (including neutrinos). Finally, there is the set of parameters emergent from cosmological considerations, which may or may not be intimately associated with particle physics questions lying ‘beyond the Standard Model’. These include the parameters defining the properties of dark matter, the baryon-to-photon ratio and the magnitude

and spectrum of the temperature fluctuations of the primordial black-body photons.

If all of these parameters are independent, and determined at best by anthropic lines of argument, the description and characterization of universes will be very difficult. As promised in the preceding sections, we shall take a more optimistic point of view and assume that at least some of them are strongly correlated. Once one of the parameters in the correlated set is specified, the others are determined.

The material that follows is a brief summary of recent work based on this point of view [2,3]. Our starting point is the consideration of the vacuum parameters defined above. One of those parameters is the coefficient of the dark-energy term in the effective action. By definition, it is different in universes of different sizes, with size defined in the previous section. As the size of a universe decreases, the dark-energy scale increases as the inverse square root of this. For Planck-sized universes, the dark energy reaches the Planck scale. For an idealized universe of infinite size, the dark energy would vanish.

We now make the basic assumption that the other vacuum parameters have a similar behaviour. For example, the QCD vacuum parameter Λ_{QCD} is assumed to vary as the inverse cube root of the size of the universe, and the electroweak condensate value v is assumed to vary as the inverse fourth root of the size. With this assumed behaviour, all these vacuum scales converge, or flow, toward a fixed point, which is of order the Planck/GUT scale in energy, when the size of the universe becomes of order the Planck/GUT size.

(A caveat: the assumed dependence of Standard Model parameters on size is with respect to the time-independent cosmological constant, *not* the FRW scale factor. We do *not* entertain here time-dependence of Standard Model parameters within our own universe, but only compare the parameters in different universes. However, a possible exception is mentioned in the final paragraph of this chapter.)

Given this assumption, more can be deduced. The dimensionless strong coupling constant α_s of QCD is determined by Λ_{QCD} . It is a ‘running coupling’, dependent upon the momentum scale probed. Since the size-dependence of this running coupling constant is determined, this is also true when the coupling constant is evaluated at the GUT scale, where it is presumably ‘unified’ with the electroweak couplings, which also ‘run’. Therefore, the size-dependence of electroweak and electromagnetic coupling constants at low-energy scales is also determined. The result is that the inverse ‘fine structure constants’, including the famous $1/137$ of quantum

electrodynamics, depend linearly on the logarithm of the size of the universe, and vanish for small Planck/GUT-scale universes. This means that the Standard Model forces are very strong and non-perturbative for such small universes, and vanish in the limit of an infinite universe. What is strongly suggested is that an infinite universe, as we have defined it, is nearly trivial, containing no Standard Model interactions whatsoever other than gravity.

It is also reasonable, albeit more uncertain, to expect that the mass parameters for the quarks and leptons follow a similar pattern, i.e. they flow to values of order the Planck/GUT scale for small universes and to zero for very large universes. But the details become increasingly fuzzy as the masses become small. In particular, the largest uncertainties occur for the anthropically significant masses, such as the electron and up-quark and down-quark masses, important for the details of nuclear physics that condition our existence. It is the lack of theoretical understanding of the basic origin of these small masses which is the roadblock.

11.4 Anthropic considerations

For better or worse, the scaling rules enunciated above allow detailed study of the physical properties of universes with sizes different from our own. This is the main content of the aforementioned ref. [2]. What is found is that the existence of chemistry is robust; the size of the universe can be varied by thirty powers of ten without major effects. In broad terms the same is true for nuclear physics. However, as is well known to the anthropic community, there are details, essential for the existence of life as we know it, which are not robust. Examination of the anthropic constraints shows that, in the context of our assumed scaling rules, the strongest limitation on the size of universes which can support life as we know it comes from the famous triple- α process, responsible for the synthesis of carbon in stars. The overall strength of the nuclear force cannot vary by more than a fraction of one per cent without causing trouble. In the case of interest, this variation is effected only via chiral symmetry-breaking, i.e. by the non-vanishing masses of the up, down and perhaps strange quarks. Those mass parameters have a different dependence on the size of the universe than does Λ_{QCD} , and it is this disparity which destroys the delicate balance of parameters which allows the triple- α reaction to proceed.

When the dust settles, the bottom line is that the size variation allowed by the existence of life as we know it is of order of a factor 2. In a universe twice as large or twice as small as ours, the Standard Model parameters would arguably be different enough to block the production of carbon in stars

and hence the evolution of life as we know it. The above estimate is quite uncertain – perhaps off by a factor of 3 or even 10. But it is accurate enough to draw a variety of tentative inferences. The most important inference has to do with the ‘hierarchy problem’, and it provides an *a posteriori* reason to take the scaling assumption seriously.

What is generally denoted by the hierarchy problem is the large disparity between the electroweak scale, characterized by the vacuum parameter v , and the Planck/GUT scale. However, it also includes the notorious ‘cosmological constant problem’: why the cosmological constant scale is thirty powers of ten smaller than the Planck/GUT scale. In addition, there is the ‘problem of mass’, which includes the issue of why the electron mass, say, is so much smaller than the top-quark mass. If the scaling behaviour is assumed, all of these questions are rendered moot. For small universes, there is no hierarchy problem; all these parameters arguably take values of order the Planck/GUT scale. And it may well be the case that the typical universe is, in fact, small. It is only because we live in such a large universe that we see these huge hierarchies of scale. The above anthropic considerations also require us to live in a large universe; the conditions for life as we know it only exist in this situation.

While this argument falls short of a full resolution of the hierarchy problem, it does provide a different way of viewing it. The problem of divergences and renormalization, which is part of the usual statement of the problem, is now expressed as the question of why the renormalized vacuum parameters should be dependent upon the size of the universe, and in the specified way. In other words, one must understand the scaling exponents such as $1/3$ and $1/4$ for the strong and electroweak sectors, respectively. This author has some ideas about the $1/3$ [3]. Others, in particular Tom Banks, have already speculated about the $1/4$ [4].

11.5 The distribution function for universes

The above considerations embolden us, perhaps foolishly, to speculate on the question of the size distribution of the universes in the ensemble, or sub-ensemble, that we have been looking at. It seems most reasonable to assume that the total number in the ensemble is finite. It also seems reasonable to assume, given the hierarchy arguments of Section 11.4, that the distribution peaks at small sizes, of order the Planck/GUT size. Given all that, the remaining question is the asymptotic behaviour at large sizes. Two natural classifications are power law and exponential. Anthropic considerations argue that the integral of the distribution over the habitable interval should

give a number large compared with unity, in order to make the universes which are in principle habitable (as we understand the term) non-unique. For any reasonable fall-off with size, such an estimate gives essentially the same result as integrating over all sizes as large or larger than our own. And it is also clear that if the fall-off is exponential or faster, the total number of universes in the sample must be gigantic, for example of order $10^{10^{60}}$. Modesty therefore suggests the alternative choice of a power-law tail. If the distribution function, $R dN/dR$, falls off at large sizes as R^{-n} , the total number of universes in the ensemble will be bounded below by a number of order 10^{60n} . This is a big number to be sure, but not very far beyond other big numbers encountered in the study of our own universe. In addition, power-law behaviour is often associated with the notion of criticality and/or scale-invariant behaviour. The feature of spatial flatness of our universe may suggest criticality as an underlying feature of a future, better theory and/or of the subset of universes with features similar to our own.

It is unrealistic to expect the ensemble of universes to be characterized by only one parameter, the size. It is therefore of interest to look at the remaining candidate parameters and search for those most likely to be ‘independently anthropic’. Amongst the Standard Model candidates, the light-quark (up and down) masses are strong ones, as forcefully advocated by Craig Hogan [5, 6]. Also, at least some subset of the three cosmological parameters mentioned in Section 11.3 seem to be strong candidates, in order that there is the right amount of large-scale structure in our universe. However, we do not have anything very new to add to this problem. Better understanding of the nature of dark matter would be of obvious help.

11.6 Concluding comments

It should be abundantly clear that the above discussion skirts dangerously close to the edge of legitimate science. Are any of these speculations falsifiable or, even better, verifiable? With regard to falsifiability, there is an answer: if the cosmological constant is eventually found to be zero, the scaling ideas die an unambiguous death. Likewise, if the cosmological constant is not constant, and exhibits a lot of quintessence, it could well be that the implied time-variation in other Standard Model parameters would exceed experimental limits. More interesting is the question of verifiability. Probably the best chance lies in finding a microscopic theory consistent with the scaling rules which has predictive power above and beyond what we now have. As mentioned in Section 11.4, there are some reasons for optimism in this regard.

It would also be advantageous if individual universes were in causal contact, which might admit experimental investigation, at least in principle. This is unlikely, and goes against the grain of almost all contemporary thinking. But it is perhaps not completely out of the realm of possibility. A few individuals, including this author, now and then entertain the notion of black hole interiors being non-singular static de Sitter space, as is the case to a good approximation for our own universe. This invites a model of the multiverse as nested black holes, with the remote possibility of two-way communication through the horizons.

Another possibility is that the ‘universe in a box’ described in Section 11.2 really consists of two universes. The first one is the inflationary universe present before ignition of the big bang. This is characterized by a huge cosmological constant (in the approximation of ‘no-roll’ instead of slow-roll). Perhaps the Standard Model parameters should take the values appropriate to the interpretation of that piece of spacetime as a ‘small universe’, with size parameter (Hubble scale) of order 10^{13} GeV (or 10^{-27} cm). It is interesting that, were this to be done, the dark-energy scale is of order the GUT scale, with the QCD and electroweak vacuum energy scales, naïvely estimated from the power-law rules, somewhat higher. It is easy to imagine that, in fact, these three scales become synthesized, and that the interpretation of the inflaton field could be in terms of QCD and/or electroweak condensates, which in turn might be more appropriately re-interpreted as a GUT condensate. The big bang would then be ignited by the ‘decay’ of the ‘small’ universe into our ‘big’ universe, accompanied somehow by a large amount of entropy production. This idea has not yet been pursued in detail. But the risk is not that this line of thinking has no phenomenological consequences, but rather that it has too many.

Acknowledgement

This work was supported by the Department of Energy contract DE-AC02-76SF00515.

References

- [1] D. Brownlee and P. Ward. *Rare Earth* (New York: Copernicus, Springer-Verlag, 1999).
- [2] J. Bjorken. *Phys. Rev. D* **67** (2003), 043508 [hep-th/0210202].
- [3] J. Bjorken. The classification of universes (2004) [astro-ph/0404233].
- [4] T. Banks. Breaking SUSY on the horizon (2002) [hep-th/0206117].
- [5] C. Hogan. *Rev. Mod. Phys* **72** (2000), 1149 [astro-ph/9909295].
- [6] C. Hogan. This volume (2007).

12

M/string theory and anthropic reasoning

Renata Kallosh

Department of Physics, Stanford University

12.1 Introduction

After the development of inflationary cosmology, anthropic reasoning (AR) became one of the most important methods in theoretical cosmology. However, until recently it was not in the toolbox of many high-energy physicists studying 11- or 10-dimensional M/string theory and supergravity. The attitude of high-energy physicists changed dramatically in 1998, when the physics community was shocked by the new cosmological observations suggesting that we may live in a world with a tiny cosmological constant, $\Lambda \sim 10^{-120} M_{\text{P}}^4$, with a weird combination of matter and dark energy.

The recent WMAP observations seem to confirm the earlier data and also support the existence of an inflationary stage in the very early Universe. In view of the accumulating observational evidence, the level of tolerance towards AR is currently increasing. More people are starting to take it into consideration when thinking about cosmology from the perspective of M/string theory and particle physics. I belong to this group, and I recently had two rather impressive encounters with AR that I would like to discuss in this chapter.

In the first encounter, Andrei Linde and I considered a model of maximal supergravity related to the 11-dimensional M-theory, which has a 4-dimensional de Sitter (dS) solution with spontaneously broken supersymmetry [1]. We found that this model offers an interesting playground for the successful application of AR. This model follows from maximal supersymmetry, and the potential $V(\phi)$ has the following important properties: (1) uniqueness; (2) $V''/V = -2$ (where a prime denotes differentiation with respect to ϕ); and (3) predictable future collapse. We found that this model suggests a possible anthropic explanation for both the present value of the cosmological constant and the observed ratio of the densities associated

with dark energy and ordinary matter. Our conclusion was based on the calculation of the lifetime of the Universe in this model and the requirement that this should be no shorter than the present age of the Universe. Although the model is far from realistic, it may still be useful as an example of how one may think about applications of AR in combination with dynamical models. In particular, if supersymmetry is discovered by the LHC in 2007, we may have to apply supersymmetric models to cosmology or impose some other bias for a dynamical model in combination with AR.

In the second (more recent) encounter with AR, Shamit Kachru, Andrei Linde, Sandip Trivedi and I [2] have looked for dS solutions in string theory that would allow us to describe the present exponential expansion of the Universe in a more traditional context, with a cosmological constant instead of quintessence. For this purpose, it was necessary to drop certain conditions for the ‘no-go’ theorems, which predicted that 4-dimensional dS space is not allowed in perturbative compactification of 11- or 10-dimensional M/string theory. We were able to achieve this through a combination of various ingredients of perturbative and non-perturbative string theory. Each of the separate contributions to the potential responsible for the appearance of dS space entered into our construction with a parameter not strictly specified by string theory but expected to lie in some plausible range. Therefore, when all the ingredients are combined to produce a dS solution, the value of the cosmological constant and the number of possible dS vacua is not prescribed uniquely. The most we can say is that dS solutions are possible and that there are many dS vacua with many values of the cosmological constant.

In any case, our current partial knowledge may lead to attempts to apply AR to the dS solutions found in string theory. Serious attempts to explain the value of the cosmological constant in string theory, using the fact that there are multiple vacua, were initiated by Bousso and Polchinski [3]. These ideas were then developed by Susskind [4] and Douglas [5] and his collaborators, in a series of papers reviewed in ref. [6]. However, Douglas prefers the term ‘vacuum selection problem’, and this includes our recently discovered dS vacua.

12.2 Anthropic constraints on Λ in $N=8$ supergravity

As a warm-up, let us first assume that the cosmological constant is large and negative, $\Lambda \ll -10^{-29} \text{ g cm}^{-3}$, as studied by Barrow and Tipler [7] and Linde [8] a long time ago. Such a model, even if flat, would collapse well before the current age of the Universe, $t_0 \sim 14 \text{ Gy}$, which would make life

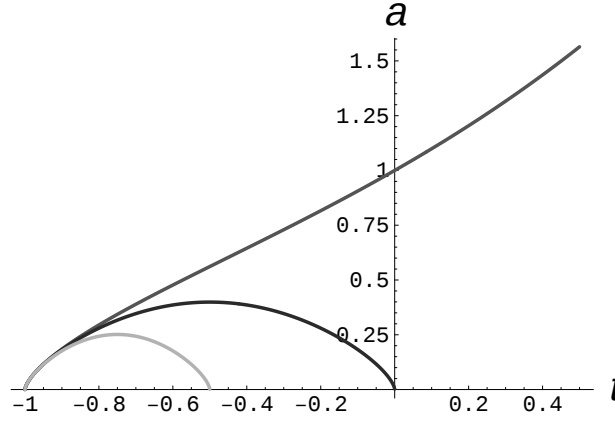


Fig. 12.1. Evolution of the cosmic scale factor a in a flat Λ CDM model for various values of Λ . Time is in units of the present age $t_0 \approx 14$ Gy. The present moment is $t = 0$ and the big bang corresponds to $t = -1$. The upper line corresponds to a flat model with $\Omega_{\text{tot}} = 1$, $\Omega_\Lambda = 0.7$ (i.e. $\Lambda = +0.7\rho_0$) and $\Omega_M = 0.3$. The middle line corresponds to a flat model with $\Lambda = -4.7\rho_0$, which collapses at the current epoch. The total lifetime of a model with $\Lambda = -18.8\rho_0$ (the lowest line) is only 7 Gy.

impossible. One may wonder whether intelligent life could emerge within 7 or 5 Gy, but we have no reason to believe this.

One may improve the earlier order-of-magnitude estimates and obtain a numerical constraint on negative Λ . The investigation is straightforward, so we simply show the results in Fig. 12.1. We find that the anthropic constraint on a negative cosmological constant is slightly less stringent than anticipated. If 7 Gy suffices for emergence of human life, then $\Lambda \gtrsim -18.8\rho_0 \sim -2 \times 10^{-28} \text{ g cm}^{-3}$. If we really need 14 Gy, the constraint is somewhat stronger: $\Lambda \gtrsim -4.7\rho_0 \sim -5 \times 10^{-29} \text{ g cm}^{-3}$.

However, the present observational data suggest that $\Lambda > 0$. In this case, the use of anthropic considerations becomes more involved, as discussed in several other contributions in this book. Here we will show that a constraint based on the total lifetime of a flat model can be derived in a class of theories based on $N=8$ supergravity that can describe the present stage of acceleration. This may allow us to avoid the fine-tuning that is usually required to explain the density parameter of the observed dark energy Ω_D .

12.2.1 Maximal supergravity as the dark energy hidden sector

No known compactifications of the fundamental M/string theory to four dimensions leads to potentials with dS solutions corresponding to $\Lambda > 0$.

Even the dS solution studied in ref. [2] does not come from the compactification of the supergravity solution alone; it requires the addition of an extended object, the anti-D3 (or $\overline{D3}$) brane, to provide a positive cosmological constant.

However, there are versions of maximally extended gauged $d=4$, $N=8$ supergravity which have dS solutions. They are also known to be solutions of $d=11$ supergravity with thirty-two supersymmetries, corresponding to M/string theory. Note that dS solutions of $d=4$, $N=8$ supergravity correspond to solutions of M/string theory with a non-compact internal 7- or 6-dimensional space. The relation between states of the higher-dimensional and four-dimensional theories in such backgrounds is complicated, since the standard Kaluza–Klein procedure is not valid in this context. It is nevertheless true that the class of $d=4$ supergravities with dS solutions that we will consider below as dark energy candidates has a direct link to M/string theory, unlike almost any other model of dark energy. Moreover, theories with maximal supersymmetry are perfectly consistent from the point of view of $d=4$ theory, all kinetic terms for scalars and vectors being positive definite.

All supersymmetries are spontaneously broken for the dS solutions of $N=8$ supergravity. These solutions are unstable; they correspond either to a maximum of the potential for the scalar fields or to a saddle point. In all known cases, one finds that there is a tachyon and the ratio between $V''=m^2$ and $V=\Lambda$ at the extremum of $V(\phi)$ is -2 . The simplest (and typical) representative of $d=4$, $N=8$ supergravity originating from M-theory with a dS maximum has the following action:

$$g^{-1/2}L = -\frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \Lambda(2 - \cosh\sqrt{2}\phi). \quad (12.1)$$

Here we use units in which the Planck mass $M_p=1$. At the critical point, we have $V'=0$, $V_{\text{cr}}=\Lambda$ and $\phi_{\text{cr}}=0$. This corresponds to $d=4$ supergravity with the gauged $SO(4,4)$ non-compact group. At the dS vacuum it breaks down to its compact subgroups, $SO(4) \times SO(4)$. The value of the cosmological constant is related to the current Hubble constant H_0 and the gauge coupling g by

$$\Lambda = 3H_0^2 = 2g^2. \quad (12.2)$$

The gauge coupling and cosmological constant in $d=4$ supergravity have the same origin in M-theory; they come from the flux of an antisymmetric tensor gauge field. The corresponding 4-form, $F_{\mu\nu\lambda\rho}$, in $d=11$ supergravity is proportional to the volume-form of the dS space:

$$F_{0123} \sim \sqrt{\Lambda} V_{0123}. \quad (12.3)$$

Here $F=dA$, where A is the 3-form potential of $d=11$ supergravity. According to this model, the small value of the cosmological constant is due to the

4-form flux, which has an inverse timescale of order the age of the Universe. Note that, in our model, there is no reason for flux quantization since the internal space is not compact. The 11-dimensional origin of the scalar field ϕ in the potential can be explained as follows: $d=4$, $N=8$ gauged supergravity has thirty-five scalars and thirty-five pseudo-scalars, together forming a coset space $E_{7(7)}/SU(8)$. The field ϕ is an $SO(4) \times SO(4)$ invariant combination of these scalars and it may also be viewed as part of the $d=11$ metric.

One's first reaction would be to discard this model altogether, because its potential is unbounded from below. However, the scalar potential in this theory remains positive for $|\phi| \lesssim 1$ and, for small Λ , the time for the development of the instability can be much greater than the present age of the Universe, which suffices for our purposes. In fact, we will see that this instability allows us to avoid the standard fine-tuning/coincidence problem which plagues most versions of quintessence theory. To use these theories to describe the present stage of acceleration (late inflation), one should take $\Lambda \sim 10^{-120} M_{\text{P}}^4$. This implies that the tachyonic mass is ultra-light, $|m^2| \sim -(10^{-33} \text{ eV})^2$.

In the early Universe the ultra-light scalar fields may stay away from the extrema of their potentials; they 'sit and wait' and begin moving only when the Hubble constant decreases enough to become comparable with the scalar mass. This may result in noticeable changes of the effective cosmological constant during the last few billion years. Since the potential of $N=8$ supergravity with a dS solution is unbounded from below, the Universe will eventually collapse. However, if the initial position of the field is not far from the top of the potential, the time for collapse may be very long.

From the perspective of $d=11$ theory, it is natural to consider a large ensemble of possible values for the fields $F \sim \sqrt{\Lambda}$ and ϕ . One may also study such an ensemble in the context of $d=4$ theory. Consider a theory of a scalar field ϕ with the effective potential given by

$$V(\phi) = \Lambda(2 - \cosh\sqrt{2}\phi) \quad (12.4)$$

in $N=8$ theory. This is illustrated in Fig. 12.2. In order to understand the cosmological consequences of this theory, let us first consider this potential at $|\phi| \ll 1$. In this limit it has the following very simple form:

$$V(\phi) = \Lambda(1 - \phi^2) = 3H_0^2(1 - \phi^2). \quad (12.5)$$

The main property of this potential is that $m^2 = V''(0) = -2\Lambda = -6H_0^2$. One can show that a homogeneous field $\phi \ll 1$ with $m^2 = -6H_0^2$ in a model with

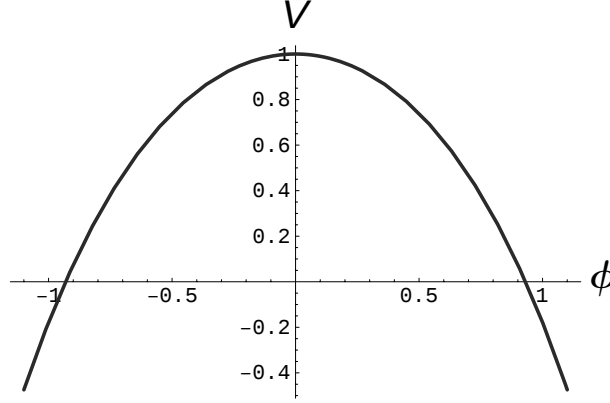


Fig. 12.2. The scalar potential $V(\phi) = \Lambda(2 - \cosh\sqrt{2}\phi)$ in $d = 4$, $N = 8$ supergravity. The value is in units of Λ and the field is in units of M_P .

Hubble constant H_0 grows as

$$\phi(t) = \phi_0 \exp(cH_0 t), \quad c = (\sqrt{33} - 3)/2 \approx 1.4. \quad (12.6)$$

Consequently, if the energy density is dominated by $V(\phi)$, it takes a time $t \sim 0.7H_0^{-1} \ln(\phi_0^{-1})$ for the scalar field to roll down from ϕ_0 to the region $\phi \gg 1$, where $V(\phi)$ becomes negative and the Universe collapses.

This means that one cannot take Λ too large without making the total lifetime of the Universe too short to support life, unless the scalar field ϕ_0 is exponentially small. But if the potential is always very flat, then the field just after inflation, ϕ_0 , can take any value with equal probability, so there is no reason to expect it to be very small. This means that, for $\phi_0 \lesssim 1$, the typical lifetime of the Universe is $t_{\text{tot}} \sim H_0^{-1} \sim \Lambda^{-1/2}$. Therefore the universe can live longer than 14 Gy only if the cosmological constant is extremely small, $\Lambda \lesssim \rho_0$. On the other hand, for $\phi \gg 1$ the potential decreases, $V(\phi) \sim -\Lambda \exp(\sqrt{2}|\phi|)$, so the Universe collapses almost instantly, even if $\Lambda \lesssim \rho_0$. Figure 12.3 shows the expansion of the Universe for $\phi_0 = 0.25$ and for various values of Λ ranging from $0.7\rho_0$ to $700\rho_0$. The time is given in units of 14 Gy. One finds, as expected, that the total lifetime of the Universe for a given ϕ_0 is proportional to $\Lambda^{-1/2}$, which means that large values of Λ are anthropically forbidden.

Figure 12.4 shows the expansion of the Universe for $\Lambda = 0.7\rho_0$. The upper line corresponds to the fiducial model with $\phi_0 = 0$. In this case, the field does not move and all cosmological consequences are as in the standard theory with the cosmological constant $\Lambda = 0.7\rho_0$. The difference will appear only in the very distant future, at $t \sim 10^2 H_0^{-1} \sim 10^3$ Gy, when the unstable state

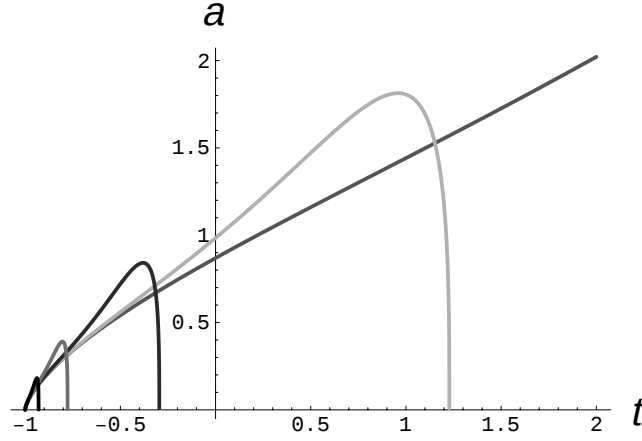


Fig. 12.3. Expansion of the Universe for $\phi_0 = 0.25$. Going from right to left, the lines correspond to $\Lambda = 0.07\rho_0$, $0.7\rho_0$, $7\rho_0$, $70\rho_0$ and $700\rho_0$.

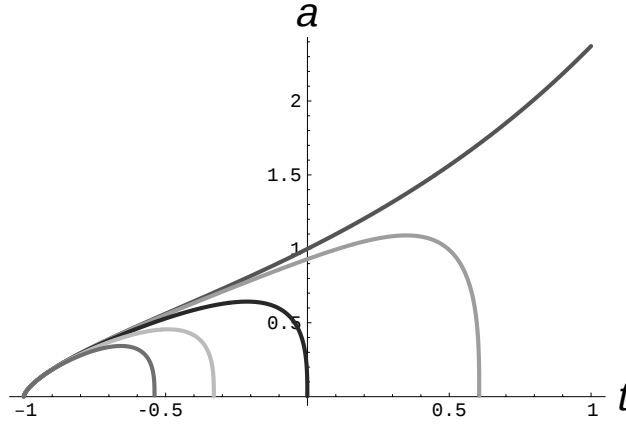


Fig. 12.4. Expansion of the Universe for $\Lambda = 0.7\rho_0$. The upper line corresponds to the fiducial model with $\phi_0 = 0$ (i.e. a cosmological constant and motionless field). The lines below this correspond successively to $\phi_0 = 0.5$, 1, 1.5 and 2.

$\phi_0 = 0$ will decay due to the destabilizing effect of quantum fluctuations. For $\phi_0 > 1$ the total lifetime of the Universe becomes unacceptably small, which means that large values of ϕ_0 are anthropically forbidden.

Further conclusions will depend on various assumptions about the probability of the parameters (Λ, ϕ_0) . We will make the simplest assumption that all values of Λ and ϕ_0 are equally probable. We will discuss alternative assumptions and their consequences in Section 12.2.2.

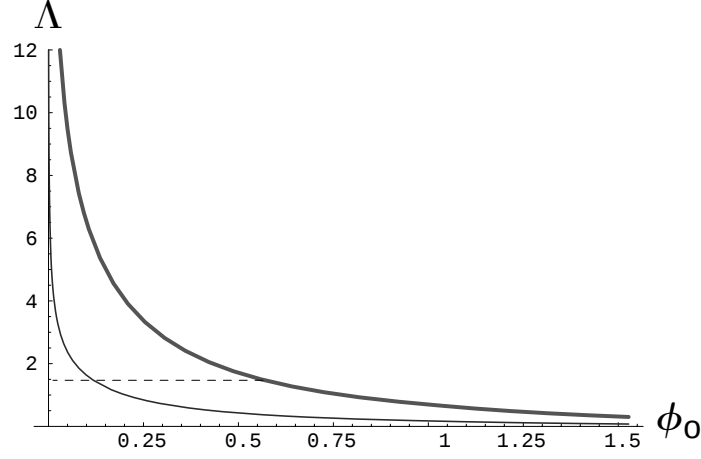


Fig. 12.5. The region below the top line corresponds to values of Λ and ϕ_0 such that the lifetime of the Universe exceeds 14 Gy. The dashed line $\Lambda \approx 1.5\rho_0$ separates this region into two equal areas. The region below the lower curve corresponds to universes with lifetime exceeding 28 Gy.

The values of Λ and ϕ_0 for which the total lifetime of the Universe exceeds 14 Gy are shown in Fig. 12.5 as the region under the thick (upper) line. If all values of Λ and ϕ_0 are equally probable, the measure of probability is given by the total area under this curve, $S_{\text{tot}} \approx 3.5$. One can estimate the probability of being in any region of the phase space (Λ, ϕ_0) by dividing the corresponding area by S_{tot} .

The dashed line $\Lambda \approx 1.5\rho_0$ separates the anthropically allowed region into two equal area parts. This implies that the average value of Λ in this theory is about $1.5\rho_0$. It is obvious that Λ can be somewhat larger or somewhat smaller than $1.5\rho_0$, but the main part of the anthropically allowed area corresponds to

$$\Lambda = O(\rho_0) \sim 10^{-120} M_{\text{P}}^4. \quad (12.7)$$

This is one of the main results of our investigation. It is a direct consequence of the relation $m^2 = -6H_0^2$, which is valid for all known versions of $d=4$, $N=8$ supergravity that allow dS solutions.

The region below the lower curve corresponds to all models with lifetimes greater than 28 Gy, i.e. to those that would live a further 14 Gy from now. The area below this curve is one-third of that between the lower and upper curves. This means that the ‘life expectancy’ of a typical anthropically allowed model (the time from the present moment until the global collapse) is smaller than the present age of the Universe. The prognosis becomes

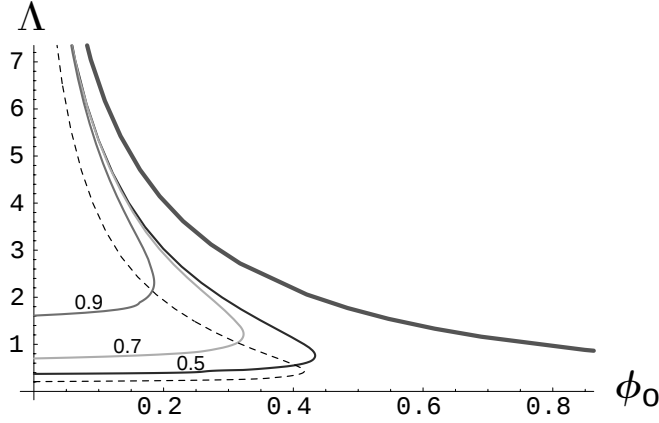


Fig. 12.6. The lifetime of the Universe exceeds 14 Gy below the top line. The other (progressively lower) curves correspond to $\Omega_D = 0.5, 0.7$ and 0.9 . The region to the right of the dashed line corresponds to universes that are accelerating now.

more optimistic if one takes into account that the Universe has $\Omega_D = 0.7$: the probability that it will survive a further 14 Gy becomes more than 50%.

The average value of Λ does not immediately tell us the most probable value of Ω_D . In order to do this, we plot in Fig. 12.6 the curves corresponding to $\Omega_D = 0.5, 0.7$ and 0.9 . The region to the right of the dashed line corresponds to models that are currently accelerating.

The total probability of living in an accelerating model 14 Gy after the big bang is determined by the area bounded by the thin dashed line in Fig. 12.6. Dividing this by $S_{\text{tot}} \approx 3.5$, one can find that this probability is about 35%. About half this area corresponds to $\Omega_D > 0.9$. The most interesting part of the accelerating region is bounded by the curves corresponding to $\Omega_D = 0.5$ and $\Omega_D = 0.9$. All points inside this region correspond to accelerating models with $0.5 < \Omega_D < 0.9$. One can see from Fig. 12.6 that the area of this region is about 0.4. Dividing this by the total area of the anthropically allowed region, $S_{\text{tot}} \approx 3.5$, one finds that the probability of living in such a model is about 10%. These results resolve the usual fine-tuning/coincidence problem.

12.2.2 More on dark energy

Most of the theories of dark energy face two problems. First, it is necessary to explain why the bare cosmological constant vanishes. Then one must find a dynamical mechanism imitating a small cosmological constant and explain why $\Omega_D \sim 0.7$ at the present cosmological epoch.

We have studied cosmological consequences of the simplest toy model of dark energy based on $N = 8$ supergravity and found that this can completely resolve the cosmological constant and coincidence problems plaguing most quintessence models. Indeed, one cannot simply add a cosmological constant to this theory. The only way to introduce something similar to the cosmological constant is to put the system close to the top of the effective potential. If the potential is very high, then it is also very curved since $V''(0) = -2V(0)$. We have found that the Universe can live long enough only if the field ϕ is initially within the Planck distance of the top, $|\phi| \lesssim M_{\text{P}}$, which is reasonable, and if $V(0)$ (which plays the role of Λ in this theory) does not much exceed the critical value $\rho_0 \sim 10^{-120} M_{\text{P}}^4$.

We made the simplest assumption that the values of Λ and ϕ_0 are uniformly distributed. However, in realistic models the situation may be different. For example, as already mentioned, $\Lambda^{1/2}$ is related to the 4-form flux in $d = 11$ supergravity from Eq. (12.3). This suggests that the probability distribution should be uniform, not with respect to Λ and ϕ_0 , but with respect to $\Lambda^{1/2}$ and ϕ_0 . We studied this possibility and found that the numerical results change, but the qualitative features of the model remain the same.

The probability distribution for ϕ_0 may be non-uniform even if $V(\phi)$ is very flat at $\phi < 1$. First, the fields with $\phi \gg 1$ (i.e. $\phi \gg M_{\text{P}}$) may be forbidden or the effective potential at large ϕ may blow up. This is often the case in $N = 1$ supergravity. Second, interactions with other fields in the early Universe may create a deep minimum, capturing the field at some time-dependent point $\phi < 1$. This also often happens in $N = 1$ supergravity, which is one of the features of the cosmological moduli problem. If it does so in our model, one can ignore the region with $\phi_0 > 1$ (the right part of Figs. 12.5 and 12.6) in the calculation of probabilities. This will increase the probability of living in an accelerating model with $0.5 < \Omega_{\text{D}} < 0.9$.

Our estimates have assumed that the Universe must live as long as 14 Gy, so that human life can appear. One could argue that the first stars and planets were formed long ago, so we may not need much more than 5–7 Gy for the development of life. This would somewhat decrease our estimate for the probability of living in an accelerating model with $0.5 < \Omega_{\text{D}} < 0.9$, but it would not alter our results qualitatively. On the other hand, most of the planets were probably formed very late in the history of the Universe, so one may argue that the probability of the emergence of human life becomes much greater at $t > 14$ Gy, especially if one keeps in mind how many other coincidences have made life possible. If one assumes that human life is extremely improbable (after all, we do not have any indications of its existence elsewhere in the Universe), then one may argue that the probability

of its emergence becomes significant only if the total lifetime of the Universe can be much greater than 14 Gy. This would increase our estimate for the probability of living in an accelerating model with $0.5 < \Omega_D < 0.9$.

So far, we have not used any considerations based on the theory of galaxy formation, as developed by Weinberg [9], Efstathiou [10], Vilenkin [11], Martel [12] and Garriga [13]. If we do so, the probability of the emergence of life for $\Lambda \gg \rho_0$ will be additionally suppressed, which will increase the probability of living in an accelerating model with $0.5 < \Omega_D < 0.9$.

To the best of my knowledge, only in models based on extended supergravity are the relation $|m^2| \sim H^2$ and the absence of freedom to add the bare cosmological constant properties of the theory rather than of a particular dynamical regime. That is why the increase of $V(\phi)$ in such models entails the increase in $|m^2|$. This, in turn, speeds up the development of the cosmological instability, which leads to anthropically unacceptable consequences.

The $N=8$ theory discussed here is just a toy model. In this case, we have been able to find a complete solution to the cosmological constant and coincidence problems (explaining why $\Lambda \sim \rho_0$ and why Ω_D noticeably differs from both zero and unity at the present stage of cosmological evolution). This model has important advantages over many other theories of dark energy, but – to make it fully realistic – one would need to construct a complete theory of all fundamental interactions, including the dark energy sector described above. This is a very complicated task, which goes beyond the scope of the present investigation. However, most of our results are not model-specific.

It would be interesting to apply our methods to models unrelated to extended supergravity. A particularly interesting model is axion quintessence. The original version had the potential given by

$$V(\phi) = \Lambda[\cos(\phi/f) + C], \quad (12.8)$$

where it was assumed that $C=1$. The positive definiteness of the potential, and the fact that it has a minimum at $V=0$, could then be motivated by global supersymmetry arguments. In supergravity and M/string theory, these arguments are no longer valid and the value of the parameter C is not specified.

In the axion model of quintessence based on M/string theory, the potential had the form $V = \Lambda \cos(\phi/f)$ without any constant. This has a maximum at $\phi=0$, $V(0)=\Lambda$. The Universe collapses when the field ϕ rolls to the

minimum of its potential, $V(f\pi) = -\Lambda$. The curvature of the effective potential at its maximum is given by

$$m^2 = -\Lambda/f^2 = -3H_0^2/f^2. \quad (12.9)$$

For $f = M_{\text{P}} = 1$, one has $m^2 = -3H_0^2$ and, for $f = M_{\text{P}}/\sqrt{2}$, one has $m^2 = -6H_0^2$, exactly as in $N = 8$ supergravity. Therefore the anthropic constraints on Λ based on the investigation of the collapse of the Universe in this model are similar to the constraints obtained in our $N = 8$ theory. However, in this model, unlike the ones based on extended supergravity, one can easily add or subtract any value of the cosmological constant. In order to obtain useful anthropic constraints on the cosmological constant, one should use a combination of our approach and the usual theory of galaxy formation.

In this sense, our main goal is not to replace the usual anthropic approach to the cosmological constant problem, but to enhance it. We find it very encouraging that our approach may strengthen the existing anthropic constraints on the cosmological constant in the context of the theories based on extended supergravity. One may find it hard to believe that, in order to explain the results of cosmological observations, one should consider theories with an unstable vacuum state. However, one should remember that exponential expansion of the Universe during inflation, as well as the process of galaxy formation, are themselves the result of the gravitational instability, so we should learn how to live with the idea that our world may be unstable.

12.3 de Sitter space in string theory

While the model discussed above is quite interesting, it is only partially related to a consistent $d = 10$ string theory. After many unsuccessful attempts to find a dS solution in string theory, we have recently come up with a class of such solutions [2]. We next outline the construction of metastable dS vacua of type IIB string theory and discuss their relation to AR.

Our starting point is the highly warped IIB compactifications with non-trivial NS and RR 3-form fluxes.¹ By incorporating known corrections to the superpotential from Euclidean D-brane instantons or gaugino condensations, one can make models with all moduli fixed, yielding a supersymmetric anti-de Sitter (AdS) vacuum. Inclusion of a small number of $\overline{\text{D3}}$ branes in the resulting warped geometry allows one to raise the AdS minimum and make it a metastable dS ground state. The lifetime of our metastable dS vacuum is much greater than the cosmological timescale of 10 Gy. We have also proven

¹ NS stands for (Neveu–Schwarz) bosonic closed string states whose left- and right-moving parts are bosonic. RR stands for (Ramond–Ramond) bosonic closed string states whose left- and right-moving parts are fermionic.

that, under certain conditions, the lifetime of dS space in string theory will always be shorter than the recurrence time.

Our basic strategy is to first freeze all the moduli present in the compactification, while preserving supersymmetry. We then add extra effects that break supersymmetry in a controlled way and lift the minimum of the potential to a positive value, yielding dS space. To illustrate the construction, we work in the specific context of IIB string theory compactified on a Calabi–Yau (CY) manifold in the presence of flux. Such constructions allow one to fix the complex structure moduli but not the Kähler moduli of the compactification. In particular, to leading order in α' and g_s , the Lagrangian possesses a no-scale structure which does not fix the overall volume.² (Henceforth we shall assume that this is the *only* Kähler modulus; it is plausible that one can construct explicit models which have this property.) In order to achieve the first step of fixing all moduli, we therefore need to consider corrections which violate the no-scale structure. Here we focus on quantum non-perturbative corrections to the superpotential, which are calculable, and show that these can lead to supersymmetry-preserving AdS vacua in which the volume modulus is fixed in a controlled manner.

Having frozen all moduli, we then introduce supersymmetry-breaking by adding a few $\overline{\text{D3}}$ branes in the compactification. The extent of supersymmetry-breaking, and the resulting cosmological constant of the dS minimum, can be varied in our construction – within certain limits – in two ways. One may vary the number of $\overline{\text{D3}}$ branes which are introduced or one may vary the warping in the compactification (by tuning the number of flux quanta through various cycles). It is important to note that this corresponds to freedom in tuning *discrete* parameters, so while fine-tuning is possible, one should not expect to be able to tune to arbitrarily high precision.

12.3.1 *Flux compactifications of IIB string theory plus corrections*

We now study a CY orientifold with flux. In such a model, one has the ‘tadpole’ consistency condition:

$$\frac{\chi(X)}{24} = N_{\text{D3}} + \frac{1}{2\kappa_{10}^2 T_3} \int_M H_3 \wedge F_3. \quad (12.10)$$

² α' is the coupling in the Nambu–Goto–Polyakov world-sheet action of the string and g_s is the string coupling itself. These two parameters control the two types of quantum corrections in string theory. The first is related to the world-sheet corrections; these correspond to higher derivative terms in the effective gravitational theory and are calculated via loop diagrams in the sigma model. The second is related to the vacuum expectation value (vev) of the dilaton which controls the corrections due to string loops; these are due to higher genus Riemann surfaces on which the string propagates.

Here T_3 is the tension of a D3 brane, N_{D3} is the net number of $(D3 - \overline{D3})$ branes one has inserted to fill the non-compact dimensions, and H_3 and F_3 are the 3-form fluxes which arise in the NS and RR sectors, respectively. We assume that we are working with a model with only one Kähler modulus, so that $h^{1,1}(M) = 1$. (In taking the F-theory limit, where one shrinks the elliptic fibre, one has $h^{1,1}(X) = 2$ and one modulus is frozen.) Such models can be explicitly constructed, for example by using the examples of CY 4-folds or by explicitly constructing orientifolds of known CY 3-folds with $h^{1,1} = 1$.

In the presence of the non-zero fluxes, one generates a superpotential for the CY moduli,

$$W = \int_M G_3 \wedge \Omega, \quad (12.11)$$

where $G_3 = F_3 - \tau H_3$ and τ is the IIB axiodilaton. Combining this with the tree-level Kähler potential,

$$K = -3 \ln[-i(\rho - \bar{\rho})] - \ln[-i(\tau - \bar{\tau})], \quad (12.12)$$

where ρ is the single volume modulus given by

$$\rho = b/\sqrt{2} + i e^{4u-\phi}, \quad (12.13)$$

and using the standard $N=1$ supergravity formula for the potential, one obtains

$$V = e^K \left(\sum_{a,b} g^{a\bar{b}} D_a W \overline{D_b W} - 3|W|^2 \right) \rightarrow e^K \left(\sum_{i,j} g^{i\bar{j}} D_i W \overline{D_j W} \right). \quad (12.14)$$

Here a and b run over all moduli fields, while i and j run over all moduli fields except ρ ; we see that, because ρ does not appear in Eq. (12.11), it cancels out of the potential energy given by Eq. (12.14), leaving the positive semi-definite potential characteristic of no-scale models. These models are not satisfactory, as they lead to the cosmological decompactification of the internal space during the cosmological evolution.

One can use two known corrections to the no-scale models, both parametrizing possible corrections to the superpotential.

- (i) In type IIB compactifications of this type, there can be corrections to the superpotential coming from Euclidean D3 branes:

$$W_{\text{inst}} = T(z_i) \exp(2\pi i \rho) \quad (12.15)$$

where $T(z_i)$ is a complex structure-dependent one-loop determinant and the leading exponential dependence comes from the action of a Euclidean D3 brane wrapping a 4-cycle in M .

- (ii) In general models of this sort, one finds non-Abelian gauge groups arising from geometric singularities in X , or (in type IIB language) from stacks of D7 branes wrapping 4-cycles in M . This theory undergoes gluino condensation, which results in a non-perturbative superpotential. This leads to an exponential superpotential for ρ similar to the one above (but with a fractional multiple of ρ in the exponent, since the gaugino condensate looks like a fractional instanton effect in W):

$$W_{\text{gauge}} = T(z_i) \exp(2\pi i \rho / N). \quad (12.16)$$

So effects (i) and (ii) have rather similar consequences for our analysis; we will simply assume that there is an exponential superpotential for ρ at large volumes. There are some interesting possibilities for cosmology if there are multiple non-Abelian gauge factors. Using the 4-folds, it is easy to construct examples which could yield gauge groups of total rank up to ~ 30 . However, much larger ranks should be possible.

The corrections to the superpotential discussed above can stabilize the volume modulus, leading to a supersymmetry Supersymmetry-preserving AdS minimum. We analyze the vacuum structure, just keeping the tree-level Kähler potential,

$$K = -3 \ln[-i(\rho - \bar{\rho})], \quad (12.17)$$

and a superpotential,

$$W = W_0 + A e^{i a \rho}, \quad (12.18)$$

where W_0 is a tree-level contribution which arises from the fluxes. The exponential term arises from either of the two sources above and the coefficient a can be determined accordingly. At a supersymmetric vacuum, we have $D_\rho W = 0$. We simplify the situation by setting the axion in the ρ modulus to zero and letting $\rho = i\sigma$. In addition, we take A, a and W_0 to be *real* and W_0 to be negative. The condition $DW = 0$ then implies that the minimum lies at

$$W_0 = -A e^{-a\sigma_{\text{cr}}} \left(1 + \frac{2}{3} a \sigma_{\text{cr}} \right). \quad (12.19)$$

The potential at the minimum is negative and equal to

$$V_{\text{AdS}} = (-3e^K W^2)_{\text{AdS}} = -\frac{a^2 A^2 e^{-2a\sigma_{\text{cr}}}}{6\sigma_{\text{cr}}}. \quad (12.20)$$

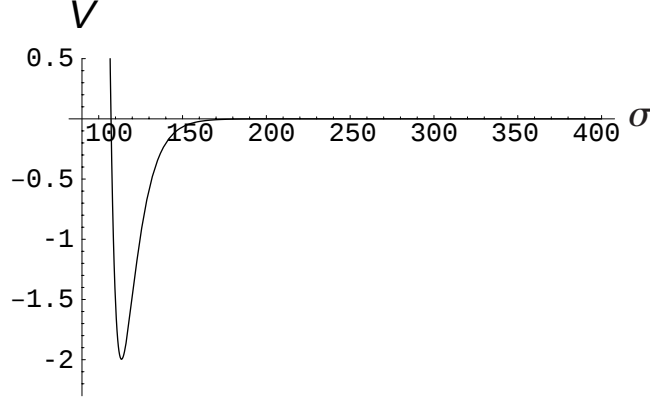


Fig. 12.7. The potential (multiplied by 10^{15}) for an exponential superpotential with $W_0 = -10^{-4}$, $A = 1$ and $a = 0.1$. In this case, there is an AdS minimum.

We see that we have stabilized the volume modulus, while preserving supersymmetry. It is important to note that the AdS minimum is quite generic. For example, if $W_0 = -10^{-4}$, $A = 1$ and $a = 0.1$, the minimum is at $\sigma_{\text{cr}} \sim 113$, as shown in Fig. 12.7.

Another possibility to obtain a minimum for large volumes is to consider a situation where the fluxes preserve supersymmetry and the superpotential involves multiple exponential terms, i.e. ‘racetrack potentials’ for the stabilization of ρ . Such a superpotential could arise from multiple stacks of 7-branes wrapping 4-cycles, which cannot be deformed into each other in a supersymmetry-preserving manner. In this case, by tuning the ranks of the gauge groups appropriately, one can obtain a parametrically large value of σ at the minimum.

Now we lift the supersymmetric AdS vacua to obtain the dS vacua of string theory. In the consistency condition given by Eq. (12.10), there are contributions from both localized D3 branes and fluxes. To find the AdS vacua with no moduli, of the kind discussed in Section 12.2, we assumed that the condition was saturated by turning on fluxes in the compact manifold.

Next we assume that, in fact, we turn on *too much* flux, so that Eq. (12.10) can only be satisfied by introducing one $\overline{\text{D3}}$ brane. The consistency equation is now satisfied due to the presence of the anti-D3 brane, but there is an extra bit of energy density from the ‘extra’ flux and $\overline{\text{D3}}$ brane. In general, we obtain a term in the potential which takes the following form:

$$\delta V = \frac{8D}{(\text{Im } \rho)^3}, \quad (12.21)$$

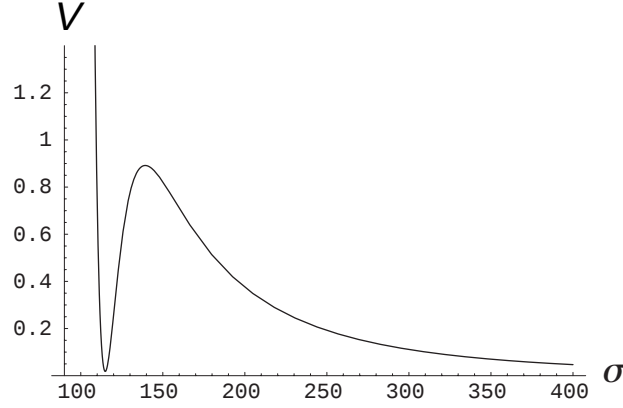


Fig. 12.8. The potential (multiplied by 10^{15}) for the case of an exponential superpotential, including a D/σ^3 correction with $D = 3 \times 10^{-9}$, which uplifts the AdS minimum to a dS minimum.

where the factor of 8 is added for later convenience. The coefficient D depends on the number of $\overline{D3}$ branes and on the warp factor at the end of the throat. These parameters can be altered by discretely changing the fluxes. This allows us to vary the coefficient D and the supersymmetry-breaking in the system, while still keeping them small. (Strictly speaking, since the flux can only be discretely tuned, D cannot be varied with arbitrary precision.) We will see that, by tuning the choice of D , one can perturb the AdS vacua to produce dS vacua with a tunable cosmological constant.

We now add to the potential a term of the form D/σ^3 , as explained above. For suitable choices of D , the AdS minimum will become a dS minimum, but the rest of the potential does not change too much. However, there is one new important feature: a dS maximum separating the dS minimum from the vanishing potential at infinity. The potential is given by

$$V = \frac{aAe^{-a\sigma}}{2\sigma^2} \left(\frac{1}{3}\sigma aAe^{-a\sigma} + W_0 + Ae^{-a\sigma} \right) + \frac{D}{\sigma^3}. \quad (12.22)$$

By fine-tuning D , it is easy to have the dS minimum very close to zero. For the model $W_0 = -10^{-4}$, $A = 1$, $a = 0.1$ and $D = 3 \times 10^{-9}$, the potential is as indicated in Fig. 12.8.

Note that, if one does not require the minimum to be so close to zero, D does not have to be so fine-tuned. A dS minimum is obtained as long as D lies within certain bounds, eventually disappearing for large enough D . If one does fine-tune to bring the minimum very close to zero, the resulting

potentials are quite steep around the dS minimum. In this circumstance, the new term effectively uplifts the potential without changing the shape too much around the minimum, so the ρ field acquires a surprisingly large mass (relative to the final value of the cosmological constant).

If one wants to use this potential to describe the present stage of acceleration of the Universe, one needs to fine-tune the value of the potential in the dS minimum to be $V_0 \sim 10^{-120}$ in units of the Planck density. In principle, one could achieve this, for example, by fine-tuning D . However, the tuning achievable by varying the fluxes in microscopic string theory is limited, though it may be possible to tune well if there are enough 3-cycles in M .

12.4 Discussion of the anthropic landscape of string theory

It is difficult to construct realistic cosmologies in string theory if the moduli fields are not frozen. We have found that it is possible to stabilize all moduli in a controlled manner in the general setting of compactification with flux. This opens up a promising arena for the construction of realistic cosmological models based on string theory. More specifically, we have seen that it is possible to construct metastable dS vacua by including anti-branes and incorporating non-perturbative corrections to the superpotential from D3 instantons or low-energy gauge dynamics.

In the simplest possible case, our examples require knowledge of at least six parameters: two to specify the distinct electric and magnetic fluxes required to fix the dilaton; three to specify the non-perturbative corrections to the superpotential; and one to specify the anti-brane contribution. Moduli stabilization in more complicated models may depend on many more parameters, which means there are many ways to realize these vacua.

One may hope that the number of vacua in string theory is very large, at least of the order $N \geq 10^{120}$. In this case, it may be possible that some of these vacua have a positive cosmological constant of order $\Lambda \sim M_{\text{P}}^4/N$, so the selection of a vacuum with $\Lambda \sim 10^{-120} M_{\text{P}}^4$ could then be anthropic. The basic estimate for the number of flux vacua, satisfying the tadpole consistency condition of Eq. (12.10), is given by Douglas [5, 6] as

$$\mathcal{N}_{\text{vac}} \sim \frac{(2\pi L)^{K/2}}{(K/2)^2}. \quad (12.23)$$

Here K is the number of distinct fluxes and $L = \chi/24$ is the ‘tadpole charge’ on the left-hand side of Eq. (12.10). The estimates are $K \sim 100\text{--}400$ and $L \sim 500\text{--}5000$, which lead to $\mathcal{N}_{\text{vac}} \sim 10^{500}$. This number is extremely large,

even larger than the number 10^{120} required for the anthropic solution of the cosmological constant problem. Each of these vacua will have a different vacuum energy density and each part of the Universe with a particular positive cosmological constant will be exponentially large. Particles living in the different vacua will have dramatically different properties.

It is interesting that all of these conclusions have been reached after the recent discovery that the Universe is accelerating. Attempts to describe this acceleration in string theory forced us to invent a way to describe dS vacua. As a result, we have found that the solution of this problem is not unique and the same string theory there could have an incredibly large number of different vacua. This explains the sudden increased attention of cosmologists and string theorists towards the concept of the multiverse and anthropic reasoning.

Acknowledgements

It is a pleasure to thank T. Banks, M. Dine, N. Kaloper, A. Klypin, L. Kofman, L. Susskind, A. Vilenkin and S. Weinberg and all my collaborators for useful discussions. This work was supported by NSF grant PHY-9870115.

References

- [1] R. Kallosh and A. Linde. M-theory, cosmological constant and anthropic principle. *Phys. Rev. D* **67** (2003), 023510.
- [2] S. Kachru, R. Kallosh, A. Linde and S. R. Trivedi. de Sitter vacua in string theory. *Phys. Rev. D* **68** (2003), 046005 [hep-th/0301240].
- [3] R. Bousso and J. Polchinski. Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. *JHEP*, **0006** (2000), 006 [hep-th/0004134].
- [4] L. Susskind. This volume (2007) [hep-th/0302219].
- [5] M. R. Douglas. The statistics of string/M theory vacua. *JHEP*, **0305** (2003), 046 [hep-th/0303194].
- [6] M. R. Douglas. Basic results in vacuum statistics. *Compt. Rend. Phys.* **5** (2004), 965 [hep-th/0409207].
- [7] J. D. Barrow and F. J. Tipler. *The Anthropic Cosmological Principle* (New York: Oxford University Press, 1986).
- [8] A. D. Linde. Inflation and quantum cosmology. In *300 Years of Gravitation*, eds. S. W. Hawking and W. Israel (Cambridge: Cambridge University Press, 1987), pp. 604–30.
- [9] S. Weinberg. Anthropic bound on the cosmological constant. *Phys. Rev. Lett.* **59** (1987), 2607.
- [10] G. Efstathiou. An anthropic argument for a cosmological constant. *Mon. Not. Roy. Astron. Soc.* **274** (1995), L73.

- [11] A. Vilenkin. Predictions from quantum cosmology. *Phys. Rev. Lett.* **74** (1995), 846 [gr-qc/9406010].
- [12] H. Martel, P. R. Shapiro and S. Weinberg. Likely values of the cosmological constant. *Astrophys. J.* **492** (1998), 29 [astro-ph/9701099].
- [13] J. Garriga and A. Vilenkin. On likely values of the cosmological constant. *Phys. Rev. D* **61** (2000), 083502 [astro-ph/9908115].

13

The anthropic principle, dark energy and the LHC

Savas Dimopoulos

Department of Physics, Stanford University

Scott Thomas

Department of Physics, Rutgers University

13.1 Naturalness versus the anthropic principle

The cosmological constant problem (CCP) is one of the most pressing problems in physics. It has eluded traditional approaches based on symmetries or dynamics. In contrast, the anthropic principle has scored a significant success in accounting for both the smallness of the cosmological constant (CC) and the proximity of the vacuum and matter energies in our universe [1].¹ Once we accept the anthropic principle as a legitimate approach for solving the CCP, it is natural to ask whether it might be applicable to other problems that can also be addressed with traditional methods. In this case, nature would have the interesting dilemma of choosing between an anthropic and a normal solution. An example is the gauge hierarchy problem (GHP). Like the CCP, it is a naturalness problem characterized by a small dimensionless number. Unlike the CCP, it can be solved with traditional symmetries, such as low-energy supersymmetry. As we will argue later, the GHP can also be addressed via anthropic arguments. So does nature choose the supersymmetric or the anthropic solution to the GHP? This question is far from academic, since the answer will be revealed experimentally by 2007 at the Large Hadron Collider (LHC).

The rise of naturalness as a principle for physics in the late 1970s led to the apparent need for a natural solution to the GHP and has convinced the majority of particle physicists that the LHC will discover either supersymmetry or another ‘natural’ theory that solves GHP. So if the LHC discovers nothing beyond the Standard Model, it will be a surprise. In our opinion, such a (non-)discovery would significantly strengthen the case for the anthropic principle and would cause a shift away from the usual

¹ For earlier related work see refs. [2] and [3]. This constraint was sharpened in ref. [4], and good reviews may be found in refs. [5] and [6].

naturalness-driven paradigm of attempting to understand the parameters of the Standard Model via symmetries or string theory. Instead, the nature of the dynamics that leads to the multiverse, and consequently provides a home for the anthropic principle, will become a primary question of physics. We now turn to this question.

13.2 Continuum and discretum

An essential hypothesis of the anthropic principle is the existence of an enormous number of universes, each with different physical laws. The collection of all these universes is called the multiverse. A major challenge is to build a compelling theory of the multiverse. There are several ideas on this and we will only mention a few. Perhaps the simplest is that there are several parallel universes, or 3-branes, all embedded inside the enormous ‘bulk’ of the space inside the large new dimensions that exist in theories with TeV-scale gravity. So the bulk is one possible home of the multiverse. It turns out that we can fit at most 10^{32} universes in the bulk, not enough to address the CCP.

Another possibility is that the fundamental theory has an enormous (but countable) number of almost stable ‘vacua’, with different values of the physical parameters. This has been coined the ‘discretum’ and may arise naturally in some versions of string theory [7–9]. A direct consequence of this discreteness is that the values of anthropically determined physical parameters, e.g. the CC, remain constant in this framework.

The third and most developed possibility, which we focus on here, is the ‘continuum’ scenario [10–13]. The idea is that a physical quantity of interest, such as the CC or the weak interaction scale, depends on a scalar field ϕ (called a ‘modulus’) which varies very slowly over length and time scales relevant to our observable universe. Nevertheless, because of the vast extent of the multiverse, the modulus (as well as the physical quantity of interest that depends on it) varies over a large continuous range of values. The canonical archetype of this sort of approach to the CCP is described by the following Lagrangian:

$$\mathcal{L} = (\partial_\mu \phi)^2 - \alpha \phi - \Lambda_0, \quad (13.1)$$

where Λ_0 is the bare CC and α has to be very small to ensure that ϕ varies slowly over spacetime scales of order those for our observable universe [14]. As a result, for any Λ_0 , there is always a hospitable domain in the Universe where the effective CC,

$$\Lambda_{\text{eff}} = \alpha \phi + \Lambda_0, \quad (13.2)$$

is adequately small for galaxies and life to form.

Possible concerns in this approach are that the Lagrangian given by Eq. (13.1) is *ad hoc* and that the extreme smallness of α is unexplained and potentially unnatural. So it is fair to wonder if this approach amounts to nothing but a complicated restatement of the CCP – even after accepting the assumption of the existence of the multiverse. A related issue is the degree of fine-tunings that we have to perform to keep the modulus ultra-light after quantum corrections are taken into account (so as to ensure that it remains overdamped and essentially motionless throughout the history of the Universe). Still other concerns are the tunings necessary to ensure that the modulus remains extremely weakly coupled to matter, as dictated by the high-precision observational tests of the Equivalence Principle. To address all these issues at once, it is convenient to consider a more general class of theories, and we discuss these next.

13.3 Large- Z moduli

Consider a modulus with the following Lagrangian [15]:

$$\mathcal{L} = Z(\partial_\mu \phi)^2 - V(\phi) + \mathcal{L}_{\text{rest}}(\phi, \text{SM}), \quad (13.3)$$

where Z is the wave-function factor of ϕ , $V(\phi)$ is its potential and $\mathcal{L}_{\text{rest}}$ is the rest of the Lagrangian (which includes all other fields of the Standard Model, as well as their couplings to ϕ). Neither $V(\phi)$ nor $\mathcal{L}_{\text{rest}}$ contains mass scales exceeding the Planck mass or any abnormally large or small new scales or dimensionless numbers.

Note that Z acts as the friction for the field ϕ . In the limit of enormous Z , ϕ freezes and does not move even on a Hubble time scale; similarly, its spatial gradients are suppressed and consequently ϕ becomes homogeneous over cosmological scales. In addition, all its couplings become enormously suppressed, including those to the Standard Model particles. Therefore, rapid exchange of ϕ -particles does not lead to violations of the Equivalence Principle. One way to see this is to rescale,

$$\phi \rightarrow \frac{1}{\sqrt{Z}} \phi, \quad (13.4)$$

and to note that all of the couplings of ϕ are now suppressed by $Z^{-1/2}$. Consequently, in the limit of enormous Z , ϕ decouples from ordinary matter and freezes, as required in order for ϕ to be a viable anthropic modulus.

Next, we come to the fundamental question of whether it is technically natural to have a large- Z modulus. This is not just an aesthetic question, since the essence of the CCP is the absence of any symmetry that could explain the vanishing (or smallness) of the CC and consequently protect it

from large radiative corrections. If the hugeness of Z were unstable against radiative corrections, then ϕ would not be a useful anthropic modulus for the CCP and this approach would just be a restatement of the CCP. However, the large value of Z is stable against radiative corrections since, in the limit of infinite Z , all but the first (kinetic) term of the Lagrangian can be neglected and the theory becomes symmetric under the global shift symmetry:

$$\phi \rightarrow \phi + C. \quad (13.5)$$

Therefore the anthropic approach allows the CC to be protected by a symmetry.

Since this is a global symmetry, it is, in principle, possible that non-perturbative quantum gravity effects break it significantly. Whether this happens or not is model-dependent and hinges on how gravity is embedded into a fundamental theory, as well as the mechanism that causes Z to be large. For example, if the string length is an order of magnitude (or more) larger than the Planck length, the violation of global symmetries is expected to be small. This is because the violation is caused by black-hole-related Planckian physics, and is screened and softened by string effects.

Finally, although this mechanism is already technically natural, it would be appealing to construct models where the large value of Z emerges from calculable dynamics. This dynamics, to be reliable, should involve physics below the Planck scale. This would ensure that the approximate global shift symmetry, $\phi \rightarrow \phi + C$, is not much affected by quantum gravity.

13.4 Large- Z moduli, the CCP and dark energy

Consider a modulus with the following Lagrangian:

$$\mathcal{L} = Z(\partial_\mu \phi)^2 - V(\phi) - \Lambda_0 - \mathcal{L}(\text{SM}), \quad (13.6)$$

where Λ_0 is the bare CC and $\mathcal{L}(\text{SM})$ is the Standard Model Lagrangian. For an anthropically viable universe, the present value of the effective CC, $\Lambda_{\text{eff}} = V(\phi) + \Lambda_0$, must not exceed the present energy density by more than an order of magnitude. Furthermore, it must not have changed much during the recent history of the Universe, else the conditions in our recent past would not have been anthropically viable.

For Z much larger than this minimum value, ϕ (and the effective CC) is frozen, resulting in a dark energy equation of state $w = -1$. This coincides with the prediction of the discretum, where again Λ_{eff} is constant. However, when Z is close to the minimum anthropically allowed value Z_{min} , ϕ can

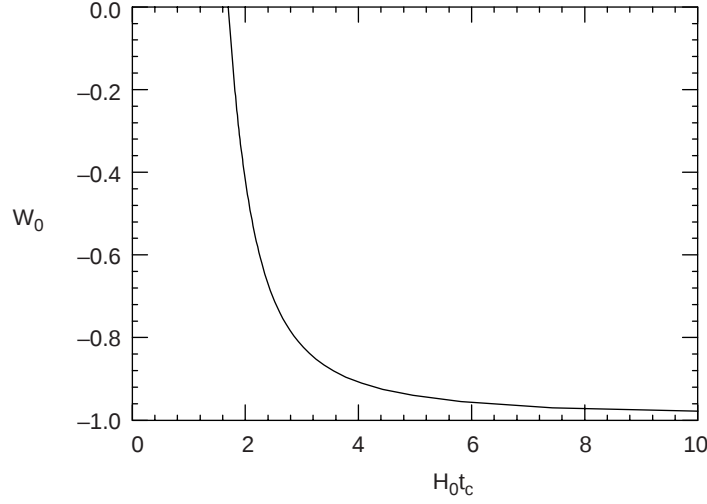


Fig. 13.1. Current value of the equation of state parameter $w_0 \equiv (p_\phi/\rho_\phi)_0$ as a function of crunch time in units of current Hubble time scale H_0^{-1} for $\Omega_m = 0.3$ and $\Omega_\phi = 0.7$.

evolve, leading to a time-dependence in Λ_{eff} and to $w \neq -1$. So, in this case, the anthropic modulus ϕ for the CCP would lead to a time-dependent equation of state for the dark energy which would have potentially testable predictions.² The premise that Z is near Z_{min} is valid for any theory in which the probability distribution for Z favours small Z .

It is easy now to see why this theory is very predictive: the hugeness of Z_{min} guarantees that ϕ does not move much during the recent history of the Universe. Therefore we can Taylor-expand the function Λ_{eff} and keep just the constant and linear parts. The constant is fixed by the magnitude of the observed dark energy. The linear part is determined by a single number (the slope), and this determines the complete time evolution of ϕ . As ϕ evolves, the vacuum energy eventually becomes negative, leading to a future big crunch. The crunch time is correlated with the current time-dependence of ϕ and therefore with the current equation of state, as illustrated in Fig. 13.1. The rate of change of the equation of state is also correlated with the current equation of state, as shown in Fig. 13.2. This correlation will be tested in future high-precision measurements of cosmic evolution, such as those from SNAP [16]. In this way, the continuum and discretum realizations of the anthropic principle can be distinguished and tested experimentally.

² General models of quintessence can also lead to a time-dependent equation of state but are not *a priori* predictive.

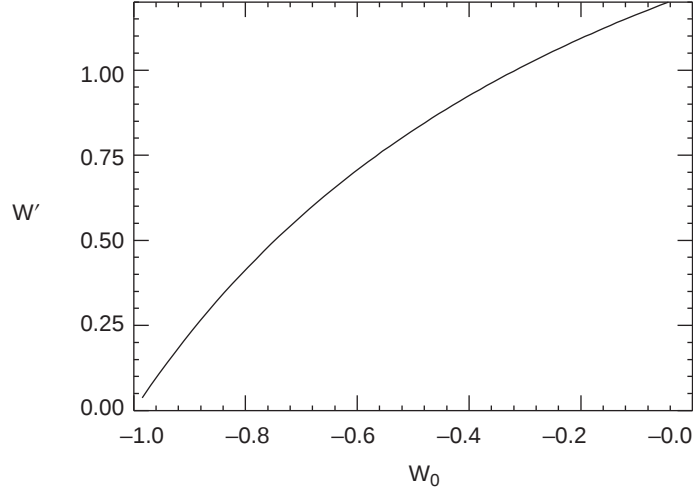


Fig. 13.2. Rate of change of the equation of state parameter $w' \equiv dw/d\ln(1+z)$, evaluated at redshift $z=1$, as a function of the current equation of state parameter $w_0 = (p_\phi/\rho_\phi)_0$ for $\Omega_m = 0.3$ and $\Omega_\phi = 0.7$.

13.5 Large- Z moduli and the hierarchy problem

Consider the Lagrangian

$$\mathcal{L} = Z(\partial_\mu \phi)^2 + [m_1^2 f(\phi) + m_2^2] H^* H, \quad (13.7)$$

where H is the usual electroweak Higgs field, the masses m_1 and m_2 are of order of the Planck scale, and $f(\phi)$ is a non-constant function of ϕ . The quantity

$$v_{\text{eff}} = \sqrt{m_1^2 f(\phi) + m_2^2} \quad (13.8)$$

is proportional to the Higgs vacuum expectation value, which in turn is proportional to the masses of all quarks, leptons and weak bosons. The smallness of the observed Higgs vacuum expectation value, $v_{\text{obs}} \sim 200$ GeV, compared with the Planck mass, $M_{\text{Pl}} \sim 10^{19}$ GeV, is the usual hierarchy problem.

Typical members of the multiverse have v_{eff} of order of the Planck mass and are consequently very different from our own. Those with v_{eff} a few times smaller than v_{obs} have protons heavier than neutrons and consequently do

not have stable hydrogen atoms. Those with v_{eff} a few times larger than v_{obs} have neutrons much heavier than protons and consequently do not have any long lived ‘heavy’ nuclei beyond hydrogen. More precisely, even small deviations of v_{eff} from v_{obs} (at the few per cent level) would change the standard carbon production in red giants. So anthropically viable universes have v_{eff} very close to v_{obs} .

The large- Z moduli anthropic approach to the hierarchy problem eliminates the need for supersymmetry, low-scale gravity, technicolour or any other natural solution to the hierarchy problem. If the LHC discovers just the Higgs, it will be concrete evidence – over and above what we now have from the CCP – in favour of the anthropic approach. It will shift the paradigm of particle physics away from explaining the parameters of the Standard Model by short-distance symmetries or string theory and towards an understanding of the enormous multiverse.

References

- [1] S. Weinberg. Anthropic bound on the cosmological constant. *Phys. Rev. Lett.* **59** (1987), 2607.
- [2] T. Banks. TCP, quantum gravity, the cosmological constant and all that. *Nucl. Phys. B* **249** (1985), 332.
- [3] A. D. Linde. Inflation and quantum cosmology. In *300 Years of Gravitation*, eds. S. Hawking and W. Israel (Cambridge: Cambridge University Press, 1987), p. 604.
- [4] A. Vilenkin. Predictions from quantum cosmology. *Phys. Rev. Lett.* **74** (1995), 846 [gr-qc/9406010].
- [5] C. J. Hogan. Why the universe is just so. *Rev. Mod. Phys.* **72** (2000), 1149 [astro-ph/9909295].
- [6] M. J. Rees. Numerical coincidences and ‘tuning’ in cosmology. In *Fred Hoyle’s Universe*, eds. C. Wickramasinghe, G. Burbidge and J. Narlikar (Dordrecht: Kluwer, 2003), pp. 95–108 [astro-ph/0401424].
- [7] R. Bousso and J. Polchinski. Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. *JHEP*, **0006** (2000), 006 [hep-th/0004134].
- [8] J. L. Feng, J. March-Russell, S. Sethi and F. Wilczek. Saltatory relaxation of the cosmological constant. *Nucl. Phys. B* **602** (2001), 307 [hep-th/0005276].
- [9] S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi. de Sitter vacua in string theory. *Phys. Rev. D* **68** (2003), 046005 [hep-th/0301240].
- [10] A. Strominger, A. Maloney and E. Silverstein. de Sitter space in noncritical string theory. In *The Future of Theoretical Physics and Cosmology*, eds. G. W. Gibbons, E. P. S. Shellard and S. J. Rankin (Cambridge: Cambridge University Press, 2003), pp. 570–591 [hep-th/0205316].
- [11] M. R. Douglas. The statistics of string/M theory vacua. *JHEP*, **0305** (2003), 046 [hep-ph/0303194].
- [12] F. Denef and M. R. Douglas. Distributions of flux vacua. *JHEP*, **0405** (2004), 072 [hep-th/0404116].

- [13] L. Susskind. This volume (2007) [hep-th/0302219].
- [14] A. D. Linde. Life after inflation and the cosmological constant problem. *Phys. Lett. B* **227** (1989), 352.
- [15] S. Weinberg. The cosmological constant problems. In *Sources and Detection of Dark Matter and Dark Energy in the Universe*, ed. D. Cline (New York: Springer-Verlag, 2001) [astro-ph/0005265].
- [16] R. Kallosh, J. Kratochvil, A. Linde, E. V. Linder and M. Shmakova. Observational bounds on cosmic doomsday. *JCAP*, **0310** (2003), 015 [astro-ph/0307185].

Part III

Particle physics and quantum theory

14

Quarks, electrons and atoms in closely related universes

Craig J. Hogan

Astronomy and Physics Departments, University of Washington

14.1 Introduction

We know that nature is governed by mathematics and symmetries. Not very long ago, it was an article of faith among most physicists that everything about physics would eventually be explained in terms of fundamental symmetries – that nothing in the make-up of physical laws is accidental, that nature ultimately has no choices, and that all the properties of particles and fields are fixed purely by mathematics.

In the thirty years since modern anthropic reasoning was introduced into cosmology [1, 2], the competing idea that anthropic selection might have an indispensable role in fundamental physical theory has gradually become, if not universally accepted, at least mainstream. There are now concrete physical models for realizing anthropic selection in nature. Cosmology has provided not only a concrete mechanism (inflation) for manufacturing multiple universes, but also a new phenomenon (dark energy) whose value is most often explained by invoking anthropic explanations. String theory has uncovered a framework by which many different symmetries and parameters for fields can be realized in the low-energy, 4-dimensional universe; this depends on the topology and size of the manifold of the other seven (truly fundamental) dimensions and on the configurations of p-branes within it, especially the local environment of the 3-brane on which our own Standard Model fields live. The number of locally metastable configurations of manifold and branes, and therefore the number of options for low-energy physics, is estimated to be so large that, for all practical purposes, there is a continuum of choices for the fundamental parameters that we observe [3–5].

Of course, the details of how this works in the real world are still sketchy. Cosmology unfolds in a series of phase transitions and symmetry-breakings. For example, it is now part of standard inflation that the quantum

wave-function of the Universe branches early into various options for the zero-point fluctuations of the inflaton field, different branches of which correspond to different distributions of galaxies. String theory opens up a scenario in which the multiverse wave-function may also branch very early into a variety of whole universes, each of which has different physics. If things happen this way, it is natural for us to find ourselves in a branch with physics remarkably well suited to make the stuff of which we are made.

It then makes sense to ask new questions about the world: how would things change if this or that aspect of physics were altered? If a small change in a certain parameter changes the world a great deal, in a way that matters to our presence here, then that is a clue that this particular parameter is fixed by selection rather than by symmetry. The following arguments along these lines are elaborated more fully in ref. [6].

Now we may be faced with a situation where some seemingly fundamental features of physics might not ever be derived from first principles. Even the particular gauge group in our Grand Unified Theory (that is, the one in our branch of the wave-function) might be only one group selected out of many options provided by the Theory of Everything. We may have to adjust our scientific style to this larger physical reality, which forces cosmology and fundamental physics into a new relationship. For example, although we cannot look inside the other universes of the multiverse ensemble and cannot predict the branching outcome from first principles, cosmological experiments now under development might reveal relict gravitational waves from the same symmetry-breaking that fixed the parameters.

14.2 Changing Standard Model parameters

Evaluating changes in the world in response to changes in the fundamental physics is actually a difficult programme to carry out. For the most fundamental theory we have, the Standard Model, the connection of many of its parameters with generally observable phenomena can only be roughly estimated. First-principle calculations of the behaviour of systems such as nuclei and molecules are possible only for the simplest examples.

The traditional minimal Standard Model has nineteen ‘adjustable’ parameters [7,8]: Yukawa coefficients fixing the masses of the six quark and three lepton flavors ($u, d, c, s, t, b, e, \mu, \tau$); the Higgs mass and vacuum expectation value v (which multiplies the Yukawa coefficients to determine the fermion masses); three angles and one phase of the CKM (Cabibbo–Kobayashi–Maskawa) matrix, which mixes quark weak and strong interaction eigenstates; a phase for the quantum chromodynamic (QCD) vacuum; and three

coupling constants g_1, g_2, g_3 of the gauge group $U(1) \times SU(2) \times SU(3)$. We now know experimentally that the neutrinos are not massless, so there are at least seven more parameters to characterize their behaviour (three masses and another four CKM matrix elements). Thus, twenty-six parameters, plus Newton's constant G and the cosmological constant Λ of general relativity, are enough to describe the behaviour of all experimentally observed particles, except perhaps those related to dark matter. If, in addition, the Standard Model is extended by supersymmetry, the number of parameters exceeds 100.

Imagine that you are sitting at a control panel of the Universe. It has a few dozen knobs – one for each of the parameters. Suppose you start twiddling the knobs. For all but a few of the knobs, you find nothing changes very much; the mass of the top quark for example (that is, its Yukawa coupling coefficient in the Standard Model equations) has little direct effect on everyday stuff.

Which knobs matter for the stuff we care about most – atoms and molecules? Some knobs are clearly important, but their exact value does not seem too critical. The fine structure constant α , for example, controls the sizes of all the atoms and molecules, these scaling like the Bohr radius $(\alpha m_e)^{-1}$. If you twiddle this knob, natural phenomena dominated by this physics – which include all of familiar chemistry and biology – grow or shrink in size. On the other hand, they all grow or shrink by roughly the same fractional amount, so the structural effect of changes is hard to notice; the miraculous fit of base-pairs into the DNA double-helix would still work quite well, for example. There are, however, subtle changes in structural relationships and molecular reaction rates. Our complicated biochemistry would probably not survive a sudden big change in α , but if you turned the knob slowly enough, living things would probably adapt to the changing physics. Simulations of cellular reaction networks show that their behaviour is remarkably robust with respect to changes in reaction rates, and mostly depend on network topology [9].

It turns out that a few of the knobs have a particularly large qualitative effect, even with a very small amount of twiddling. Three knobs stand out for their particularly conspicuous effects: the Yukawa coefficients controlling the masses of the electron, the up-quark and the down-quark. These are the light fermions that dominate the composition and behaviour of atoms and molecules. Changing them by even a small fractional amount has a devastating effect on whether molecules can exist at all. The most dramatic sensitivity of the world on their values seems to be in the physics of atomic nuclei.

14.3 Effects of changing u, d, e masses on atoms and nuclei

The light fermion masses are all very small compared with the mass of a proton (less than one per cent). (Ironically, the mass of protons and neutrons, which comprise the bulk of the mass of ordinary matter, is dominated not by the ‘real mass’ of their constituent quarks, but almost entirely by the kinetic energies of the quarks and the massless gluons mediating the colour forces.) However, the light fermion masses are critical because they determine the energy thresholds for reactions that control the stability of nucleons.

In the 3-dimensional parameter space formed by these masses, the most reliable phenomenological statements can be made about changes within the 2-dimensional surface defined by holding the sum of the u and d masses constant. (That is because many complicated features of nuclear physics remain constant if the pion mass, which is proportional to $(m_u + m_d)^{1/2}$, is constant.) In this plane, some properties of worlds with different values of the masses are summarized in Figs. 14.1 and 14.2, the latter having been taken from ref. [2]. The figures also show a constraint for a particular $SO(10)$ grand unified scenario, to illustrate that likely unification schemes probably do not leave all these parameters independent – at least one relationship between them is likely fixed by unification symmetry.

In the lower part of Fig. 14.1, towards larger up-quark mass, there are ‘neutron worlds’. As one turns the knobs in this direction, a threshold is soon crossed where it is energetically favourable for the electron in a hydrogen atom to join with its proton to make a neutron. If you turn it farther, even a free proton (without any nearby electron) spontaneously decays into a neutron. In the upper part of the figure, there are ‘proton worlds’. Moving up from our world, a threshold is soon crossed where a deuteron in a plasma is no longer energetically favoured over a pair of protons. If you go farther, even an isolated deuteron spontaneously decays into a pair of protons.

In the neutron world, there are nuclei, but not atoms with electrons around them, so chemistry does not happen. In the proton world, there are hydrogen atoms, but they are the only kind of atoms because the other nuclei do not form or are not stable. Fortunately for us there is a world in between, where a few dozen stable nuclei are both possible and are actually produced in stars, and are endowed with electron orbitals leading to chemistry with arbitrarily large and complex molecules. This world would disappear with only a few per cent fractional change in the quark mass difference in either direction. It does not exist in some closely related branches of the multiverse wave-function.

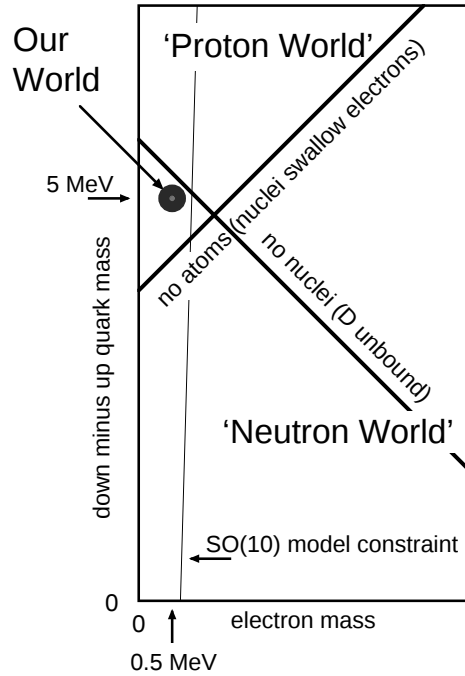


Fig. 14.1. An overview of the simple nuclear physics of the neutron, proton and deuteron, in other universes closely related to ours. Thresholds for various reactions are shown in terms of the mass difference between the down and up quarks and the electron mass, in the plane where the sum of the up and down masses does not change. Our world is shown by the dot. The $SO(10)$ constraint shown imposes the restriction that the ratio of electron to down quark mass is fixed by a symmetry to have the same value as it does in the real world; the region to the right of this is excluded for positive down-quark mass.

One can estimate roughly the effects of leaving this plane. In that case, nuclear physics is changed in new ways, since the mass of the pion changes. It appears that if the masses are increased by more than about 40%, the range of nuclear forces is reduced to the point where the deuteron is unstable; and if they are reduced by a similar amount, the nuclear forces are strengthened to the point where the diproton is stable. On the other hand, the latter change also reduces the range of nuclear forces, so that there are fewer stable elements overall. The sum of the quark masses in our world appears roughly optimized for the largest number of stable nuclei. Again, the situation would change qualitatively (for example, far fewer stable elements) with changes in summed quark masses at the 10% level.

Why is it even possible to find parameters balanced between the neutron world and the proton world? For example, if the $SO(10)$ model is

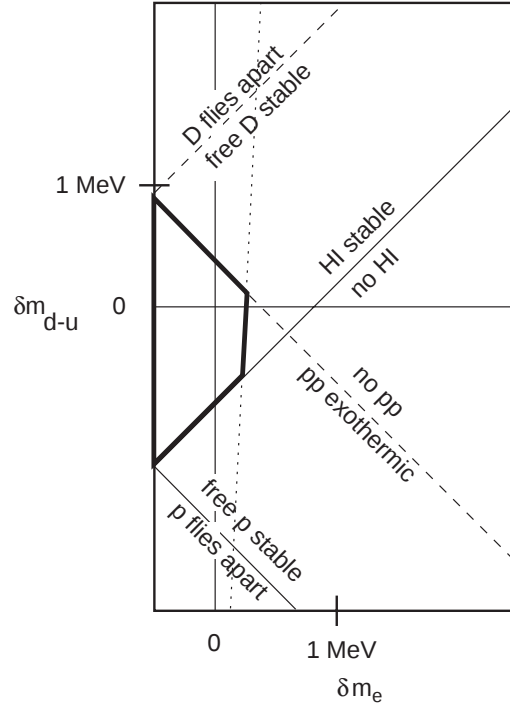


Fig. 14.2. A more detailed view, from ref. [2], of the changes in thresholds of nuclear reactions, as a function of the change in the u, d mass difference and the change in the electron mass. Our world is at the origin in these quantities.

the right one, it seems that we are lucky that its trajectory passes through the region that allows for molecules. The answer could be that even the gauge symmetries and particle content have an anthropic explanation. A great variety of compact 7-manifolds and 3-brane configurations solve the fundamental M-theory. Each one of them has dimensional scales, corresponding to parameter values such as particle masses, as well as topological and geometrical relationships corresponding to symmetries. Many of these configurations undergo inflation and produce macroscopic universes. In this situation, it is not surprising that we find ourselves in one where atoms and nuclei can exist.

14.4 Quantum mechanics and anthropic selection

Discussions of anthropic selection have sometimes differentiated between the kind that selects whole universes (with different values of the electron mass etc.) and the kind that selects a congenial environment (why we do not

live on an asteroid or a quasar etc.) While these seem very different from a quantum-mechanical perspective, they do not differ in kind. Both involve selections of a congenial branch of the wave-function of the Universe.

In the original formulation of quantum mechanics, it was said that an observation collapsed a wave-function to one of the eigenstates of the observed quantity. The modern view is that the cosmic wave-function never collapses, but only appears to collapse from the point of view of observers who are part of the wave-function. When Schrödinger's cat lives or dies, the branch of the wave-function with the dead cat also contains observers who are dealing with a dead cat, and the branch with the live cat also contains observers who are petting a live one.

Although this is sometimes called the 'many worlds' interpretation of quantum mechanics, it is really about having just one world, with one wave-function obeying the Schrödinger equation: the wave-function evolves linearly from one time to the next, based on its previous state. Anthropic selection in this sense is built into physics at the most basic level of quantum mechanics. Selection of a wave-function branch is what drives us into circumstances in which we thrive. Viewed from a disinterested perspective outside the Universe, it is as though living beings swim like salmon up their favourite branches of the wave-function, chasing their favourite places.

The selection of a planet or a galaxy is a matter of chance. In quantum mechanics, this means that a branch of the wave-function has been selected. The binding energy of our galaxy was determined by an inflaton fluctuation during inflation; that was when the branching occurred that selected the large-scale gravitational potential that set the parameters for our local cosmic environment. We can achieve statistical understanding about this kind of selection because we can observe other parts of the ensemble, by observing galaxy clustering, the microwave background and so on. In this way, we understand the physics of the symmetry-breaking. We even know something about the formation of the different galaxy distributions in other universes that we will never see. These are regarded as being just different by chance.

If the quark and electron masses are also matters of chance, the branching of the wave-function occurred along with the symmetry-breaking that fixed their masses. There may be ways to observe aspects of the statistical ensemble for this event also, by studying the gravitational-wave background rather than the microwave background.

We do not know when all the choices of parameters and symmetries were made. Some of these branchings may leave traces of other choices observable

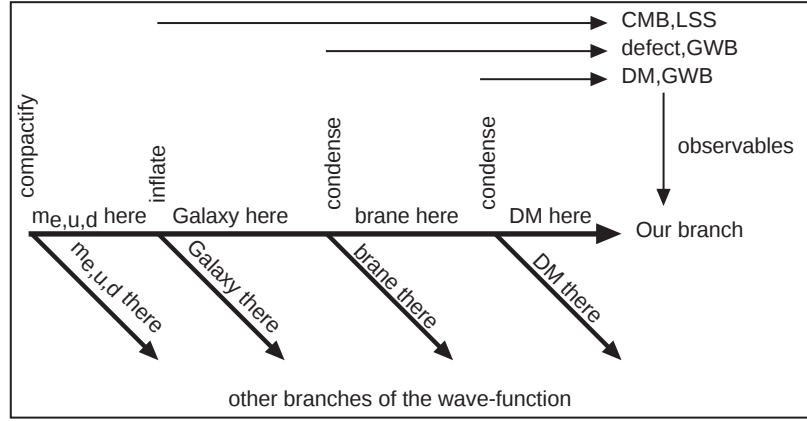


Fig. 14.3. A schematic sketch of the branching history of the wave-function to which we belong. At various points in cosmic history, symmetry-breaking (for example compactification, inflation, condensation) made random choices, which were frozen into features such as Standard Model parameters, the galaxy distribution, or the dark matter (DM) density. In some cases, these events left other observables which can be observed directly in other ways, such as cosmic microwave background (CMB) anisotropy, large-scale structure (LSS), gravitational-wave backgrounds (GWB) or cosmic defects. Thus, although the other branches of the wave-function cannot be observed directly, the physics of the branching events in some situations may be independently observable.

in our past light cone, as illustrated in Fig. 14.3. It could be that some parameters are spatially varying even today, in response to spatial variations in scalar or dark matter fields. For example, one model of dark energy predicts large variations in the masses of neutrinos, depending on the local density of the neutrino component of dark matter [10]. (Indeed, the basic idea that effective neutrino masses depend on the local physical environment is now part of the standard theory of solar neutrino oscillations.) Thus the properties of stars can be spatially modulated, depending on the dark matter density – a quantity determined, in many theories, by a branching event that occurred recently enough to have an observable effect. Such ideas provide a new motivation for observational programmes to quantify the extent to which the constants of nature are really constant in spacetime. (A thriving example of this can be found in studies of varying α .)

In some models, events connected with fixing the local quark and electron masses may have happened late enough to leave fossil traces. This could happen during the final compactification of some of the extra dimensions, or the condensation of our own Standard Model 3-dimensional brane within a larger-dimensional space. If compactification happens in a sufficiently

catastrophic symmetry-breaking, it can lead to a background of gravitational waves. Because they are so penetrating, gravitational waves can carry information directly from almost the edge of our past light-cone, well beyond recombination, even beyond weak decoupling – indeed back to the edge of 3-dimensional space as we know it.

If the extra dimensions are smaller than the Hubble length at dimensional compactification or brane condensation, their collapse can appear as a first-order phase transition in our 3-dimensional space, leading to relativistic flows of mass-energy. If the extra dimensions are larger than or comparable to the Hubble scale, our 3-dimensional brane may initially condense with warps and wiggles that lead to a gravitational wave background. Either way, the mesoscopic, classical motion of branes settling down to their final equilibrium configuration could lead to a strong gravitational-radiation background in a frequency range detectable by detectors now under development [11–14]. Thus, instruments designed to observe the early boundary of spacetime may also explore the early boundary of physics as we know it, and directly test ideas concerning the separation of various branches of the multiverse having different fundamental parameters.

This blending of empirical cosmology and fundamental physics is reminiscent of our Darwinian understanding of the tree of life. The double-helix, the four-base codon alphabet and the triplet genetic code for amino acids, any particular gene for a protein in a particular organism – all these are frozen accidents of evolutionary history. It is futile to try to understand or explain these aspects of life, or indeed any relationships in biology, without referring to the way the history of life unfolded. In the same way that – in Dobzhansky’s phrase [15] – ‘nothing in biology makes sense except in the light of evolution’, physics in these models only makes sense in the light of cosmology.

Acknowledgement

This work was supported by NSF grant AST-0098557 at the University of Washington.

References

- [1] B. Carter. Large number coincidences and the anthropic principle in cosmology. In *Confrontation of Cosmological Theory with Observational Data*, ed. M. S. Longair (Dordrecht: Reidel, 1974), p. 291.
- [2] B. J. Carr and M. J. Rees. The anthropic principle and the structure of the physical world. *Nature*, **278** (1979), 605.

- [3] R. Bousso and J. Polchinski. Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. *JHEP*, **0006** (2000), 006 [hep-th/0004134].
- [4] S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi. de Sitter vacua in string theory. *Phys. Rev. D* **68** (2003), 046005 [hep-th/0301240].
- [5] L. Susskind. This volume (2007) [hep-th/0302219].
- [6] C. J. Hogan. Why the universe is just so. *Rev. Mod. Phys.* **72** (2000), 1149 [astro-ph/9909295].
- [7] R. N. Cahn. The eighteen arbitrary parameters of the standard model in your everyday life. *Rev. Mod. Phys.* **68** (1996), 951.
- [8] M. K. Gaillard, P. D. Grannis and F. J. Sciulli. The standard model of particle physics. *Rev. Mod. Phys.* **71** (1999), 596.
- [9] E. M. Munro and G. Odell. Morphogenetic pattern formation during ascidian notochord formation is regulative and highly robust. *Development*, **129** (2002), 1.
- [10] R. Fardon, A. E. Nelson and N. Weiner. Dark energy from mass varying neutrinos. *J. Cosmol. Astropart. Phys.*, **0410** (2004), 005 [astro-ph/0309800].
- [11] C. J. Hogan. Scales of the extra dimensions and their gravitational wave backgrounds. *Phys. Rev. D* **62** (2000), 121302 [astro-ph/0009136].
- [12] C. J. Hogan. Gravitational waves from mesoscopic dynamics of the extra dimensions. *Phys. Rev. Lett.* **85** (2000), 2044 [astro-ph/0005044].
- [13] C. J. Hogan and P. L. Bender. Estimating stochastic gravitational wave backgrounds with Sagnac calibration. *Phys. Rev. D* **64** (2001), 062002 [astro-ph/0104266].
- [14] K. Ichiki and K. Nakamura. Stochastic gravitational wave background in brane world cosmology. (2004) [astro-ph/0406606].
- [15] T. Dobzhansky. *Am. Biol. Teacher*, **345** (1973), 125.

15

The fine-tuning problems of particle physics and anthropic mechanisms

John F. Donoghue

Department of Physics, University of Massachusetts

15.1 Open questions in particle physics

Each field has a set of questions which are universally viewed as important, and these questions motivate much of the work in the field. In particle physics, several of these questions are directly related to experimental problems. Examples include questions such as: Does the Higgs boson exist and, if so, what is its mass? What is the nature of the dark matter seen in the Universe? What is the mechanism that generated the net number of baryons in the Universe? For these topics, there is a well posed problem related to experimental findings or theoretical predictions. These are problems that must be solved if we are to achieve a complete understanding of the fundamental theory.

There also exists a different set of questions which have a more aesthetic character. In these cases, it is not as clear that a resolution is required, yet the problems motivate a search for certain classes of theories. Examples of these are the three ‘naturalness’ or ‘fine-tuning’ problems of the Standard Model; these are associated with the cosmological constant Λ , the energy scale of electroweak symmetry-breaking v and the strong CP-violating angle θ . As will be explained more fully below, these are free parameters in the Standard Model that seem to have values 10 to 120 orders of magnitude smaller than their natural values and smaller than the magnitude of their quantum corrections. Thus their ‘bare’ values plus their quantum corrections need to be highly fine-tuned in order to obtain the observed values. Because of the magnitude of this fine-tuning, one suspects that there is a dynamical mechanism at work that makes the fine-tuning natural. This motivates many of the theories of new physics beyond the Standard Model. A second set of aesthetic problems concern the parameters of the Standard Model, i.e. the coupling constants and masses of

the theory. While the Standard Model is constructed simply using gauge symmetry, the parameters themselves seem not to be organized in any symmetric fashion. We would love to uncover the principle that organizes the quark and lepton masses (sometimes referred to as the ‘flavour problem’), for example, but attempts to do so with symmetries or a dynamical mechanism have been unsuccessful.

These aesthetic questions are very powerful motivations for new physics. For example, the case for low energy supersymmetry, or other TeV scale dynamics to be uncovered at the Large Hadron Collider (LHC), is based almost entirely on the fine-tuning problem for the scale of electroweak symmetry-breaking. If there is new physics at the TeV scale, then there need not be any fine-tuning at all and the electroweak scale is natural. We are all greatly looking forward to the results of the LHC, which will tell us if there is in fact new physics at the TeV scale. However, the aesthetic questions are of a different character from direct experimental ones concerning the existence and mass of the Higgs boson. There does not *have* to be a resolution to the aesthetic questions – if there is no dynamical solution to the fine-tuning of the electroweak scale, it would puzzle us, but would not upset anything within the fundamental theory. We would just have to live with the existence of fine-tuning. However, if the Higgs boson is not found within a given mass range, it would falsify the Standard Model.

The idea of a multiverse will be seen to change drastically the way in which we perceive the aesthetic problems of fine-tuning and flavour. In a multiverse, the parameters of the theory vary from one domain to another. This naturally leads to the existence of anthropic constraints – only some of these domains will have parameters that reasonably allow the existence of life. We can only find ourselves in a domain which satisfies these anthropic constraints. Remarkably, the anthropic constraints provide plausible ‘solutions’ to two of the most severe fine-tuning problems: those of the cosmological constant and the electroweak scale. Multiverse theories also drastically reformulate some of the other problems – such as the flavour problem. However, at the same time, these theories raise a new set of issues for new physics. My purpose in this chapter is to discuss how the idea of the multiverse reformulates the problems of particle physics.

It should be noted up front that the Anthropic Principle [1–3] has had a largely negative reputation in the particle physics community. At some level this is surprising – a community devoted to uncovering the underlying fundamental theory might be expected to be interested in exploring a suggestion as fundamental as the Anthropic Principle. I believe that the problem really lies in the word ‘Principle’ more than in the word ‘Anthropic’.

The connotation of ‘Principle’ is that of an underlying theory. This leads to debates over whether such a principle is scientific, i.e. whether it can be tested. However, ‘anthropics’ is not itself a theory, nor even a principle. Rather, the word applies to constraints that naturally occur within the full form of certain physical theories. However, it is the theory itself that needs to be tested, and to do this one needs to understand the full theory and pull out its predictions. For theories that lead to a multiverse, anthropic constraints are unavoidable. As we understand better what types of theory have this multiverse property, the word anthropic is finding more positive applications in the particle physics community. This article also tries to describe some of the ways that anthropic arguments can be used to positive effect in particle physics.

15.2 The golden Lagrangian and its parameters

The Lagrangian of the Standard Model (plus General Relativity) encodes our present understanding of all observed physics except for dark matter [4]. The only unobserved ingredient of the theory is the Higgs boson. The Standard Model is built on the principle of gauge symmetry – that the Lagrangian has an $SU(3) \otimes SU(2)_L \otimes U(1)$ symmetry at each point of spacetime. This, plus renormalizability, is a very powerful constraint and uniquely defines the structure of the Standard Model up to a small number of choices, such as the number of generations of fermions. General Relativity is also defined by a gauge symmetry – local coordinate invariance. The resulting Lagrangian can be written in compact notation:

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4}F^2 + \bar{\psi}iD\psi + \frac{1}{2}D_\mu\phi D^\mu\phi \\ & + \bar{\psi}\Gamma\psi\phi + \mu^2\phi^2 - \lambda\phi^4 - \frac{1}{16\pi G_N}R - \Lambda. \end{aligned} \quad (15.1)$$

Experts recognize the various terms here as indications of the equations governing the photon, gluons and W-bosons (the F^2 terms), quarks and leptons (the ψ terms), the Higgs field (ϕ) and gravity (R), along with a set of interactions constrained by the gauge symmetry. Of course, such a simple form belies a very complex theory, and tremendous work is required to understand the predictions of the Standard Model. But the greatest lesson of particle physics of the past generation is that nature organizes the Universe through a simple set of gauge symmetries.

However, the story is not complete. The simple looking Lagrangian given by Eq. (15.1), and the story of its symmetry-based origin, also hide a far less

beautiful fact. To *really* specify the theory, we need not only the Lagrangian, but also a set of twenty-eight numbers which are the parameters of the theory. These are largely hidden underneath the compact notation of the Lagrangian. Examples include the masses of all the quarks and leptons (including neutrinos), the strengths of the three gauge interactions, the weak mixing angles describing the charge current interactions of quarks and leptons, the overall scale of the weak interaction, the cosmological constant and Newton's gravitational constant. None of these parameters is predicted by the theory. The values that have been uncovered experimentally do not obey any known symmetry pattern, and the Standard Model provides no principle by which to organize them. After the beauty of the Standard Model Lagrangian, these seemingly random parameters reinforce the feeling that there is more to be understood.

15.3 Fine-tuning

Three of the twenty-eight parameters are especially puzzling, because their values appear to be unnaturally small. Naturalness and fine-tuning have very specific technical meanings in particle physics. These meanings are related to, but not identical to, the common usage in non-technical settings. The technical version is tied to the magnitude of quantum corrections. When one calculates the properties of any theory using perturbation theory, quantum mechanical effects give additive corrections to all its parameters. Perturbation theory describes the various quantities of a theory as a power series in the coupling constants. The calculation involves summing over the effects of all virtual states that are possible in the theory, including those at high energy. The quantum correction refers to the terms in the series that depend on the coupling constants. The 'bare' value is the term independent of the coupling constants. The physical measured value is the sum of the bare value and the quantum corrections.

The concept of naturalness is tied to the magnitude of the quantum corrections. If the quantum correction is of the same order as (or smaller than) the measured value, the result is said to be natural. If, on the contrary, the measured value is much smaller than the quantum correction, then the result is unnatural because the bare value and the quantum correction appear to have an unexpected cancellation to give a result that is much smaller than either component. This is an unnatural fine-tuning.

In fact, the quantum correction is often not precisely defined. The ambiguity can arise due to possible uncertainties of the theory at high energy. Since physics is an experimental science, and we are only gradually uncovering

the details of the theory as we probe higher energies, we do not know the high energy limits of our present theory. We expect new particles and interactions to be uncovered as we study higher energies. Since the quantum correction includes effects from high energy, there is an uncertainty about their extent and validity. We understand the theory up to some energy – let us call this E_{max} – but beyond this new physics may enter. The quantum corrections will typically depend on the scale E_{max} . We will see below that, in some cases, the theory may be said to be natural if one employs low values of E_{max} but becomes unnatural for high values.

The Higgs field in the Standard Model takes a constant value everywhere in spacetime. This is called its ‘vacuum expectation value’, abbreviated as vev, which has the magnitude $v = 246$ GeV. This is the only dimensionful constant in the electroweak interactions and hence sets the scale for all dimensionful parameters of the electroweak theory. For example, all of the quark and lepton masses are given by dimensionless numbers Γ_i (the Yukawa couplings) times the Higgs vev, $m_i = \Gamma_i v / \sqrt{2}$. However, the Higgs vev is one of the parameters which has a problem with naturalness. While it depends on many parameters, the problem is well illustrated by its dependence on the Higgs coupling to the top quark. In this case, the quantum correction grows quadratically with E_{max} . One finds

$$v^2 = v_0^2 + \frac{3\Gamma_t^2}{4\pi^2\lambda} E_{\text{max}}^2, \quad (15.2)$$

where Γ_t is the Yukawa coupling for the top quark, v_0 is the bare value, λ is the self-coupling of the Higgs and the second term is the quantum correction. Since $v = 246$ GeV and $\Gamma_t \sim \lambda \sim 1$, this would be considered natural if $E_{\text{max}} \sim 10^3$ GeV, but it would be unnatural by twenty-six orders of magnitude if $E_{\text{max}} \sim 10^{16}$ GeV (characteristic of the Grand Unified Theories which unite the electroweak and strong interactions) or thirty-two orders of magnitude if $E_{\text{max}} \sim 10^{19}$ GeV (characteristic of the Planck mass, which sets the scale for quantum gravity).

If we philosophically reject fine-tuning and require that the Standard Model be technically natural, this requires that E_{max} should be around 1 TeV. For this to be true, we need a new theory to enter at this scale that removes the quadratic dependence on E_{max} in Eq. (15.2). Such theories do exist – supersymmetry is a favourite example. Thus the argument against fine-tuning becomes a powerful motivator for new physics at the scale of 1 TeV. The LHC has been designed to find this new physics.

An even more extreme violation of naturalness involves the cosmological constant Λ . Experimentally, this dimensionful quantity is of order $\Lambda \sim (10^{-3} \text{ eV})^4$. However, the quantum corrections to it grow as the fourth power of the scale E_{max} :

$$\Lambda = \Lambda_0 + cE_{\text{max}}^4, \quad (15.3)$$

with the constant c being of order unity. This quantity is unnatural for all particle physics scales by a factor of 10^{48} for $E_{\text{max}} \sim 10^3 \text{ GeV}$ to 10^{124} for $E_{\text{max}} \sim 10^{19} \text{ GeV}$.

It is unlikely that there is a technically natural resolution to the cosmological constant's fine-tuning problem – this would require new physics at 10^{-3} eV . A valiant attempt at such a theory is being made by Sundrum [5], but it is highly contrived to have new dynamics at this extremely low scale which modifies only gravity and not the other interactions.

Finally, there is a third classic naturalness problem in the Standard Model – that of the strong CP-violating parameter θ . It was realized that QCD can violate CP invariance, with a free parameter θ which can, in principle, range from zero up to 2π . An experimental manifestation of this CP-violating effect would be the existence of a non-zero electric dipole moment for the neutron. The experimental bound on this quantity requires $\theta \leq 10^{-10}$. The quantum corrections to θ are technically infinite in the Standard Model if we take the cut-off scale E_{max} to infinity. For this reason, we would expect that θ is a free parameter in the model of order unity, to be renormalized in the usual way. However, there is a notable difference from the two other problems above in that, if the scale E_{max} is taken to be very large, the quantum corrections are still quite small. This is because they arise only at a very high order in perturbation theory. So, in this case, the quantum corrections do not point to a particular scale at which we expect to find a dynamical solution to the problem.

15.4 Anthropic constraints

The standard response to the fine-tuning problems described above is to search for dynamical mechanisms that explain the existence of the fine-tuning. For example, many theories for physics beyond the Standard Model (such as supersymmetry, technicolour, large extra dimensions, etc.) are motivated by the desire to solve the fine-tuning of the Higgs vev. These are plausible, but as yet have no experimental verification. The fine-tuning problem for the cosmological constant has been approached less successfully; there are few good suggestions here. The strong CP problem has motivated

the theory of axions, in which an extra symmetry removes the strong CP violation, but requires a very light pseudo-scalar boson – the axion – which has not yet been found.

However, theories of the multiverse provide a very different resolution of the two greatest fine-tuning problems, that of the Higgs vev and the cosmological constant. This is due to the existence of anthropic constraints on these parameters. Suppose for the moment that life can only arise for a small range of values of these parameters, as will be described below. In a multiverse, the different domains will have different values of these parameters. In some domains, these parameters will fall in the range that allows life. In others, they will fall outside this range. It is then an obvious constraint that we can only observe those values that fall within the viable range. For the cosmological constant and the Higgs vev, we can argue that the anthropic constraints only allow parameters in a very narrow window, all of which appears to be fine-tuned by the criteria of Section 15.3. Thus the observed fine-tuning can be thought to be required by anthropic constraints in multiverse theories.

The first application of anthropic constraints to explain the fine-tuning of the cosmological constant – even before this parameter was known to be non-zero – was due to Linde [6] and Weinberg [7]; see also refs. [8–10]. In particular, Weinberg gave a physical condition – noting that, if the cosmological constant was much different from what it is observed to be, galaxies could not have formed. The cosmological constant is one of the ingredients that governs the expansion of the Universe. If it had been of its natural scale of $(10^3 \text{ GeV})^4$, the Universe would have collapsed or been blown apart (depending on the sign) in a fraction of a second. For the Universe to expand slowly enough that galaxies can form, Λ must lie within roughly an order of magnitude of its observed value. Thus the 10^{124} orders of magnitude of fine-tuning is spurious; we would only find ourselves in one of the rare domains with a tiny value of the cosmological constant.

Other anthropic constraints can be used to explain the fine-tuning of the Higgs vev. In this case, the physical constraint has to do with the existence of atoms other than hydrogen. Life requires the complexity that comes from having many different atoms available to build viable organisms. It is remarkable that these atoms do not exist for most values of the Higgs vev, as has been shown by my collaborators and myself [11,12]. Suppose for the moment that all the parameters of the Standard Model are held fixed, except for v which is allowed to vary. As v increases, all of the quark masses grow, and hence the neutron and proton masses also increase. Likewise, the neutron–proton mass-splitting increases in a calculable fashion. The most

model-independent constraint on v then comes from the value when the neutron–proton mass-splitting becomes larger than the 10 MeV per nucleon that binds the nucleons into nuclei; this occurs when v is about five times the observed value. When this happens, all bound neutrons will decay to protons [11, 12]. However, a nucleus of only protons is unstable and will fall apart into hydrogen. Thus complex nuclei will no longer exist.

A tighter constraint takes into account the calculation of the nuclear binding energy, which decreases as v increases. This is because the nuclear force, especially the central isoscalar force, is highly dependent on pion exchange and, as v increases, the pion mass also increases, making the force of shorter range and weaker. In this case, the criteria for the existence of heavy atoms require v to be less than a few times its observed value. Finally, a third constraint – of comparable strength – comes from the need to have deuterium stable, because deuterium was involved in the formation of the elements in primordial and stellar nucleosynthesis [11, 12]. In general, even if the other parameters of the Standard Model are not held fixed, the condition is that the weak and strong interactions must overlap. The masses of quarks and leptons arise in the weak interactions. In order to have complex elements, some of these masses must be lighter than the scale of the strong interactions and some heavier. This is a strong and general constraint on the electroweak scale. All of these constraints tell us that the viable range for the Higgs vev is not the thirty or so orders of magnitude described above, but only the tiny range allowed by anthropic constraints.

15.5 Lack of anthropic constraints

While anthropic constraints have the potential to solve the two greatest fine-tuning problems of the Standard Model, similar ideas very clearly fail to explain the naturalness problem of the strong CP-violating parameter θ [4]. For any possible value of θ in the allowed range from 0 to 2π , there would be little influence on life. The electric dipole moments that would be generated could produce small shifts in atomic energy levels but would not destabilize any elements. Even if a mild restriction could be found, there would be no logical reason why θ should be as small as 10^{-10} . Therefore the idea of a multiverse does nothing to solve this fine-tuning problem.

The lack of an anthropic solution to this problem is a very strong constraint on multiverse theories. It means that, in a multiverse ground state that satisfies the other anthropic constraints, the strong CP problem must *generically* be solved by other means. Perhaps the axion option, which appears to us to be an optional addition to the Standard Model, is in fact

required to be present for some reason – maybe in order to generate dark matter in the Universe. Or perhaps there is a symmetry that initially sets θ to zero, in which case the quantum corrections shift it only by a small amount. This can be called the ‘small infinity’ solution, because – while the quantum correction is formally infinite – it is small when any reasonable cut-off is used. Thus the main problem in this solution is to find a reason why the bare value of θ is zero rather than some number of order unity. In any case, in multiverse theories the strong CP problem appears more serious than the other fine-tuning problems and requires a dynamical solution.¹

15.6 Physical mechanisms

The above discussion can be viewed as a motivation for multiverse theories. Such theories would provide an explanation of two of the greatest puzzles of particle physics. However, this shifts the focus to the actual construction of such physical theories. So far we have just presented a ‘story’ about a multiverse. It is a very different matter to construct a real physical theory that realizes this story.

The reason that it is difficult to construct a multiverse theory is that most theories have a single ground state, or at most a small number of ground states. It is the ground state properties that determine the parameters of the theory. For example, the Standard Model has a unique ground state, and the value of the Higgs vev in that state determines the overall scale for the quark masses etc. Sometimes theories with symmetries will have a set of discretely different ground states, but generally just a few. The utility of the multiverse to solve the fine-tuning problems requires that there be *very* many possible ground states. For example, if the cosmological constant has a fine-tuning problem of a factor of 10^{50} , one would expect that one needs of order 10^{50} different ground states with different values of the cosmological constant in order to have the likelihood that at least one of these would fall in the anthropically allowed window.

In fact, such theories do exist, although they are not the norm. There are two possibilities: one where the parameters vary continuously and one where they vary in discrete steps. In the former case, the variation of the parameters in space and time must be described by a field. Normally such a field would settle into the lowest energy state possible, but there is a mechanism whereby the expansion of the Universe ‘freezes’ the value of the field and does not let it relax to its minimum [14–16]. However, since

¹ Chapter 3 of this volume by Wilczek, [13] suggests a possible anthropic explanation in the context of inflationary models for why θ should be very small.

the present expansion of the Universe is very small, the forces acting on this field must be exceptionally tiny. There is a variant of such a theory which has been applied to the fine-tuning of the cosmological constant. However, it has proven difficult to extend this theory to the variation of other parameters.

A more promising type of multiverse theory appears to be emerging from string theory. This originates as a 10- or 11-dimensional theory, although in the end all but four of the spacetime dimensions must be rendered unobservable to us, for example by being of very tiny finite size. Most commonly, the extra dimensions are ‘compact’, which means that they are of finite extent but without an endpoint, in the sense that a circle is compact. However, solutions to string theory seem to indicate that there are very many low energy solutions which have different parameters, depending on the size and shape of the many compact dimensions [17–21]. In fact, there are so many that one estimate puts the number of solutions that have the properties of our world – within the experimental error bars for all measured parameters – as of order 10^{100} . There would then be many more parameters outside the possible observed range. In this case, there are astonishingly many possible sets of parameters for solutions to string theory. This feature of having fantastically many solutions to string theory, in which the parameters vary as you move through the space of solutions, is colloquially called the ‘landscape’.

There are two key properties of these solutions. The first is that they are discretely different and not continuous [22]. The different states are described by different field values in the compact dimensions. These field values are quantized, because they need to return to the same value as one goes around the compact dimension. With enough fields and enough dimensions, the number of solutions rapidly becomes extremely large.

The second key property is that transitions between the different solutions are known [23–25]. This can occur when some of the fields change their values. From our 4-dimensional point of view, what occurs is that a bubble nucleates, in which the interior is one solution and the exterior is another one. The rate for such nucleations can be calculated in terms of string theory parameters. In particular, it apparently always occurs during inflation or at finite temperature. Nucleation of bubbles commonly leads to large jumps in the parameters, such as the cosmological constant, and the steps do not always go in the same direction.

These two properties imply that a multiverse is formed in string theory if inflation occurs. There are multiple states with different parameters, and transitions between these occur during inflation. The outcome is a universe

in which the different regions – the interior of the bubble nucleation regions – have the full range of possible parameters.

String theorists long had the hope that there would be a unique ground state of the theory. It would indeed be wonderful if one could prove that there is only one true ground state and that this state leads to the Standard Model, with exactly the parameters seen in nature. It would be hard to imagine how a theory with such a high initial symmetry could lead only to a world with parameters with as little symmetry as seen in the Standard Model, such as $m_u = 4$ MeV, $m_d = 7$ MeV, etc. But if this were in fact shown, it would certainly prove the validity of string theory. Against this hope, the existence of a landscape and a multiverse seems perhaps disappointing. Without a unique ground state, we cannot use the prediction of the parameters as a proof of string theory.

However, there is another sense in which the string theory landscape is a positive development. Some of us who are working ‘from the bottom up’ have been led by the observed fine-tuning (in both senses of the word) to desire the existence of a multiverse with exactly the properties of the string theory landscape. From this perspective, the existence of the landscape is a strong motivation in favour of string theory, more immediate and pressing even than the desire to understand quantum gravity.

Inflation also seems to be a necessary ingredient for a multiverse [26–28]. This is because we need to push the boundaries between the domains far outside our observable horizon. Inflation neatly explains why we see a mostly uniform universe, even if the greater multiverse has multiple different domains. The exponential growth of the scale factor during inflation makes it reasonable that we see a uniform domain. However, today inflation is the ‘simple’ ingredient that we expect really does occur, based on the evidence of the flatness of the universe and the power spectrum of the cosmic microwave background temperature fluctuations. It is the other ingredient of the multiverse proposal – having very many ground states – that is much more difficult.

15.7 Testing through a full theory

Let us be philosophical for a moment. Anthropic arguments and invocations of the multiverse can sometimes border on being non-scientific. You cannot test for the existence of other domains in the Universe outside the one visible to us – nor can you find a direct test of the Anthropic Principle. This leads some physicists to reject anthropic and multiverse ideas as being outside of the body of scientific thought. This appears to me to be unfair. Anthropic

consequences appear naturally in some physical theories. However, there are nevertheless non-trivial limitations on what can be said in a scientific manner in such theories.

The resolution comes from the realization that neither the anthropic nor the multiverse proposal constitutes a concrete theory. Instead there are real theories, such as string theory, which have a multiverse property and lead to our domain automatically satisfying anthropic constraints. These are not vague abstractions, but real physical consequences of real physical theories. In this case, the anthropic and multiverse proposals are not themselves a full theory but rather the output of such a theory. Our duty as scientists is not to give up because of this but to find other ways to test the original theory. Experiments are reasonably local and we need to find some reasonably local tests that probe the original full theory.

However, it has to be admitted that theories with a multiverse property, such as perhaps the string landscape – where apparently ‘almost anything goes’ – make it difficult to be confident of finding local tests. Perhaps there are some consequences which always emerge from string theory for all states in the landscape. For example, one might hope that the bare strong CP-violating θ angle is always zero in string theory and that it receives only a small finite renormalization. However, other consequences would certainly be of a statistical nature that we are not used to. An example is the present debate as to whether supersymmetry is broken at low energy or high energy in string theory. It is likely that both possibilities are present, but the number of states of one type is likely to be very different (by factors of perhaps 10^{100}) from the number of states of the other type – although it is not presently clear which is favoured. If this is solved, it will be a good statistical prediction of string theory. If we can put together a few such statistical predictions, we can provide an effective test of the theory.

15.8 A test using quark and lepton masses

Of the parameters of the Standard Model, none are as confusing as the masses of the quarks and leptons. From the history of the periodic table and atomic/nuclear spectroscopy, we would expect that the masses would show some pattern that reveals the underlying physics. However, no such pattern has ever been found. In this section, I will describe a statistical pattern, namely that the masses appear randomly distributed with respect to a scale-invariant weight, and I will discuss how this can be the probe of a multiverse theory.

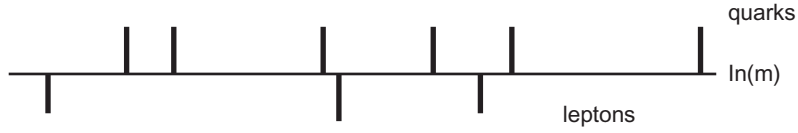


Fig. 15.1. The quark and lepton masses on a log scale. The result appears to be qualitatively consistent with a random distribution in $\ln m$, and quantitative analysis bears this out.

In a multiverse or in the string theory landscape, one would not expect the quark and lepton masses to exhibit any pattern. Rather, they would be representative of one of the many possible states available to the theory. Consider the ensemble of ground states which have the other parameters of the Standard Model held fixed. In this ensemble, the quark and lepton masses are not necessarily uniformly distributed. Rather we could describe their distribution by some *weight* [29,30]. For example, perhaps this weight favours quarks and leptons with small masses, as is in fact seen experimentally. We would then expect that the quark masses seen in our domain are not particularly special but are typical of a random distribution with respect to this weight.

The quark masses appear mostly at low energy, yet extend to high energy. To pull out the range of weights that could lead to this distribution involves a detailed study of their statistical properties. Yet it is remarkably easy to see that they are consistent with being scale-invariant. A scale-invariant weight means that the probability of finding the masses in an interval dm at any mass m scales as dm/m . This in turn means that the masses should be randomly distributed when plotted as a function of $\ln m$. It is easy to see visually that this is the case; Fig. 15.1 shows the quark and lepton masses plotted on a logarithmic scale. One can readily see that this is consistent with being a random distribution. The case for a scale-invariant distribution can be quantified by studying the statistics of six or nine masses distributed with various weights [30]. When considering power-law weights of the form dm/m^δ , one can constrain the exponent δ to be greater than 0.8. The scale-invariant weight ($\delta = 1$) is an excellent fit. One may also discuss the effects of anthropic constraints on the weights [30].

What should we make of this statistical pattern? In a multiverse theory, this pattern is the visible remnant of the underlying ensemble of ground states of different masses. An example of how this distribution could appear from a more fundamental theory is given by the Intersecting Brane Worlds solutions of string theory [31,32]. In these solutions, our 4-dimensional

world appears as the intersection of solutions (branes) of higher dimension, much as a 1-dimensional line can be described as the intersection of two 2-dimensional surfaces. In these theories, the quark and lepton masses are determined by the area between three intersections of these surfaces. In particular, the distribution is proportional to the exponential of this area, $m \sim e^{-A}$. In a string landscape there might not be a unique area, but rather a distribution of areas. The mathematical connection is that, if these areas are distributed uniformly (i.e. with a constant weight), then the masses are distributed with a scale-invariant weight. In principle, the distribution of areas is a calculation that could be performed when we understand string theory better. Thus, we could relate solutions of string theory to the observed distribution of masses in the real world. This illustrates how we can test the predictions of a multiverse theory without a unique ground state.

15.9 Summary

The idea of a multiverse can make positive contributions to particle physics. In a multiverse, some of our main puzzles disappear, but they are replaced by new questions.

We have seen how the multiverse can provide a physical reason for some of the fine-tuning that seems to be found in nature. We have also stressed that two distinct meanings of the phrase ‘fine-tuning’ are used in different parts of the scientific literature. One meaning, often encountered in discussions of anthropic considerations, relates to the observation that the measured parameters seem to be highly tuned to the narrow window that allows life to exist. The other meaning is the particle physics usage described above, which concerns the relative size of the quantum corrections compared with the measured value. The latter usage has no *a priori* connection to the former. However, the idea of the multiverse unites the two uses – the requirement of life limits the possible range of the particle physics parameters and can explain why the measured values are necessarily so small compared with the quantum effects.

However, in other cases, the multiverse makes the problems harder. The strong CP problem is not explained by the multiverse. It is a clue that a dynamical solution to this problem has to be a generic feature of the underlying full theory.

The flavour problem of trying to understand the properties of the quarks and leptons also becomes reformulated. I have described how the masses appear to be distributed in a scale-invariant fashion. In a multiverse theory,

it is possible that this is a reflection of the dynamics of the underlying theory and that this feature may someday be used as a test of the full theory.

We clearly have more to discover in particle physics. In answering the pressing experimental questions on the existence of the Higgs boson and the nature of dark matter etc., we will undoubtedly learn more about the underlying theory. We also hope that the new physics that emerges will shed light on aesthetic questions concerning the Standard Model. The idea of the multiverse is a possible physical consequence of some theories of physics beyond the Standard Model. It has not been heavily explored in particle physics, yet presents further challenges and opportunities. We clearly have more work to do before we can assess how fruitful this idea will be for the theory of the fundamental interactions.

Acknowledgements

I am pleased to thank my collaborators on these topics, Steve Barr, Dave Seckel, Thibault Damour, Andreas Ross and Koushik Dutta, as well as my long-term collaborator on more sensible topics, Gene Golowich, for discussions that have helped shape my ideas on this topic. My work has been supported in part by the US National Science Foundation and by the John Templeton Foundation.

References

- [1] J. Barrow and F. Tipler. *The Anthropic Cosmological Principle* (Oxford: Clarendon Press, 1986).
- [2] C.J. Hogan. Why the universe is just so. *Rev. Mod. Phys.* **72** (2000), 1149 [astro-ph/9909295].
- [3] R. N. Cahn. The eighteen arbitrary parameters of the standard model in your everyday life. *Rev. Mod. Phys.* **68** (1996), 951.
- [4] J. F. Donoghue, E. Golowich and B. R. Holstein. *Dynamics of the Standard Model* (Cambridge: Cambridge University Press, 1992).
- [5] R. Sundrum. Towards an effective particle-string resolution of the cosmological constant problem. *JHEP*, **9907** (1999), 001 [hep-ph/9708329].
- [6] A. Linde. Inflation and quantum cosmology. In *Results and Perspectives in Particle Physics*, ed. M. Greco (Gif-sur-Yvette, France: Editions Frontières, 1989), p. 11.
- [7] S. Weinberg. Theories of the cosmological constant. In *Critical Dialogues in Cosmology*, ed. N. Turok (Singapore: World Scientific, 1997).
- [8] H. Martel, P. R. Shapiro and S. Weinberg. Likely values of the cosmological constant. *Astrophys. J.*, **492** (1998), 29 [astro-ph/9701099].
- [9] T. Banks, M. Dine and L. Motl. On anthropic solutions of the cosmological constant problem. *JHEP*, **0101** (2001), 031 [hep-th/0007206].
- [10] J. D. Bjorken. Standard model parameters and the cosmological constant. *Phys. Rev. D* **64** (2001), 085008 [hep-ph/0103349].

- [11] V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel. Anthropic considerations in multiple-domain theories and the scale of electroweak symmetry breaking. *Phys. Rev. Lett.* **80** (1998), 1822 [hep-ph/9801253].
- [12] V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel. The anthropic principle and the mass scale of the standard model. *Phys. Rev.* **D57** (1998), 5480 [hep-ph/9707380].
- [13] F. Wilczek. This volume (2007).
- [14] J. Garriga and A. Vilenkin. On likely values of the cosmological constant. *Phys. Rev.* **D 61** (2000), 083502 [astro-ph/9908115].
- [15] J. Garriga and A. Vilenkin. Solutions to the cosmological constant problems. *Phys. Rev.* **D 64** (2001), 023517 [hep-th/0011262].
- [16] J. F. Donoghue. Random values of the cosmological constant. *JHEP* **0008** (2000), 022 [hep-ph/0006088].
- [17] M. R. Douglas. The statistics of string M theory vacua. *JHEP*, **0305** (2003), 046 [hep-th/0303194].
- [18] S. Ashok and M. R. Douglas. Counting flux vacua. *JHEP*, **0401** (2004), 060 [hep-th/0307049].
- [19] L. Susskind. This volume (2007) [hep-th/0302219].
- [20] T. Banks, M. Dine and E. Gorbatov. Is there a string theory landscape? *JHEP*, **0408** (2004), 058 [hep-th/0309170].
- [21] R. Kallosh and A. Linde. M-theory, cosmological constant and anthropic principle. *Phys. Rev.* **D 67** (2003), 023510 [hep-th/0208157].
- [22] R. Bousso and J. Polchinski. Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. *JHEP*, **0006** (2000), 006 [hep-th/0004134].
- [23] J. D. Brown and C. Teitelboim. Neutralization of the cosmological constant by membrane creation. *Nucl. Phys.* **B 297** (1988), 787.
- [24] J. D. Brown and C. Teitelboim. Dynamical neutralization of the cosmological constant. *Phys. Lett.* **B 195** (1987), 177.
- [25] J. F. Donoghue. Dynamics of M-theory vacua. *Phys. Rev.* **D 69** (2004), 106012; erratum 129901 [hep-th/0310203].
- [26] A. D. Linde. Eternally existing self-reproducing chaotic inflationary universe. *Phys. Lett.* **B 175** (1986), 395.
- [27] A. D. Linde. Eternal chaotic inflation. *Mod. Phys. Lett.* **A 1** (1986), 81.
- [28] A. H. Guth. Inflation and eternal inflation. *Phys. Rep.* **333** (2000), 555 [astro-ph/0002156].
- [29] J. F. Donoghue. The weight for random quark masses. *Phys. Rev.* **D 57** (1998), 5499 [hep-ph/9712333].
- [30] J. F. Donoghue, K. Dutta and A. Ross. Quark and lepton masses in the landscape. *Phys. Rev.* **D 73** (2006), 113002.
- [31] D. Cremades, L. E. Ibanez and F. Marchesano. Towards a theory of quark masses, mixings and CP-violation. (2002) [hep-ph/0212064].
- [32] D. Cremades, L. E. Ibanez and F. Marchesano. Yukawa couplings in intersecting D-brane models. *JHEP*, **0307** (2003), 038 [hep-th/0302105].

16

The anthropic landscape of string theory

Leonard Susskind

Department of Physics, Stanford University

16.1 The landscape

The world-view shared by most physicists is that the laws of nature are uniquely described by some special action principle that completely determines the vacuum, the spectrum of elementary particles, the forces and the symmetries. Experience with quantum electrodynamics and quantum chromodynamics suggests a world with a small number of parameters and a unique ground state. For the most part, string theorists bought into this paradigm. At first, it was hoped that string theory would be unique and explain the various parameters that quantum field theory left unexplained. When this turned out to be false, the belief developed that there were exactly five string theories with names like ‘type 2a’ and ‘heterotic’. This also turned out to be wrong. Instead, a continuum of theories were discovered that smoothly interpolated between the five and also included a theory called ‘M-theory’. The language changed a little. One no longer spoke of different theories, but rather of different solutions of some master theory.

The space of these solutions is called the ‘moduli space of supersymmetric vacua’. I will call it the ‘supermoduli-space’. Moving around on this supermoduli-space is accomplished by varying certain dynamical ‘moduli’. Examples of moduli are the size and shape parameters of the compact internal space that 4-dimensional string theory always needs. These moduli are not parameters in the theory, but are more like fields. As you move around in ordinary space, the moduli can vary and have their own equations of motion. In a low-energy approximation, the moduli appear as massless scalar fields. The beauty of the supermoduli-space point of view is that there is only one theory but many solutions, these being characterized by the values of the scalar field moduli. The mathematics of string theory is so precise that it is hard to believe that there is not a consistent mathematical framework underlying the supermoduli-space vacua.

However, the continuum of solutions in the supermoduli-space are all supersymmetric, with exact super-particle degeneracy and vanishing cosmological constant. Furthermore, they all have massless scalar particles – the moduli themselves. Obviously, none of these vacua can possibly be our world. Therefore the string theorist must believe that there are other discrete islands lying off the coast of the supermoduli-space. The hope now is that a single non-supersymmetric island or at most a small number of islands exist and that non-supersymmetric physics will prove to be approximately unique. This view is not inconsistent with present knowledge (indeed it is possible that there are *no* such islands), but I find it completely implausible. It is much more likely that the number of discrete vacua is astronomical, measured not in millions or billions but in googles or googleplexes.¹

This change in viewpoint is demanded by two facts, one observational and one theoretical. The first is that the expansion of the Universe is accelerating. The simplest explanation is a small but non-zero cosmological constant. Evidently we have to expand our thinking about vacua to include states with non-zero vacuum energy. The incredible smallness and apparent fine-tuning of the cosmological constant makes it absurdly improbable to find a vacuum in the observed range unless there are an enormous number of solutions with almost every possible value. It seems to me inevitable that, if we find one such vacuum, we will find a huge number of them. I will from now on call the space of all such string theory vacua the *landscape*.

The second fact is that some recent progress has been made in exploring the landscape [1, 2]. Before explaining the new ideas, I need to define more completely what I mean by the landscape. The supermoduli-space is parameterized by the moduli, which we can think of as a collection of scalar fields Φ_n . Unlike the case of Goldstone bosons, points in the moduli space are not related by a symmetry of the theory. Generically, in a quantum field theory, changing the value of a non-Goldstone scalar involves a change of potential energy. In other words, there is a non-zero field potential $V(\Phi)$. Local minima of V are what we call vacua. If the local minimum is an absolute minimum, the vacuum is stable. Otherwise it is only meta-stable. The value of the potential energy at the minimum is the cosmological constant for that vacuum.

To the extent that the low-energy properties of string theory can be approximated by field theory, similar ideas apply. Bearing in mind that the low-energy approximation may break down in some regions of the landscape,

¹ A google is defined to be 10 to the power 100; that is $\mathcal{G} = 10^{100}$. A googleplex is $10^{\mathcal{G}}$.

I will assume the existence of a set of fields and a potential. The space of these fields is the landscape.

The supermoduli-space is a special part of the landscape where the vacua are supersymmetric and the potential $V(\Phi)$ is exactly zero. These vacua are marginally stable and can be excited by giving the moduli arbitrarily small time derivatives. On the supermoduli-space the cosmological constant is also exactly zero. Roughly speaking, the supermoduli-space is a perfectly flat plain at exactly zero altitude.² Once we move off the plain, supersymmetry is broken and a non-zero potential develops, usually through some non-perturbative mechanism. Thus, beyond the flat plain, we encounter hills and valleys. We are particularly interested in the valleys, where we find local minima of V . Each such minimum has its own vacuum energy. The typical value of the potential difference between neighbouring valleys will be some fraction of M_p^4 , where M_p is the Planck mass. The potential barriers between minima will be of similar height. Thus, if a vacuum is found with cosmological constant of order $10^{-120} M_p^4$, it will be surrounded by much higher hills and other valleys.

Next consider two large regions of space, each of which has the scalars in some local minimum, the two minima being different. If the local minima are landscape neighbours, then the two regions of space will be separated by a domain wall. Inside the domain wall the scalars go over a ‘mountain pass’. The interior of the regions are vacuum-like with cosmological constants. The domain wall, which can also be called a membrane, has additional energy in the form of a membrane tension. Thus there will be configurations of string theory which are not globally described by a single vacuum but instead consist of many domains separated by domain walls. Accordingly, the landscape in field space is reflected in a complicated terrain in real space.

There are scalar fields that are not usually thought of as moduli, but – once we leave the flat plain – I do not think there is any fundamental difference. These are the 4-form field strengths, first introduced in the context of the cosmological constant by Brown and Teitelboim [3]. A simple analogy exists to help visualize these fields and their potential. One can think of 1 + 1-dimensional electrodynamics³ with an electric field E and massive electrons. The electric field is constant in any region of space where there are no charges. The field energy is proportional to the square of the field strength. The electric field jumps by a quantized unit whenever an electron is passed. Going in one direction, say along the positive x axis, the field makes a

² By ‘altitude’ I am referring to the value of V .

³ In 1 + 1 dimensions there is no magnetic field and the electric field is a 2-form, aka a scalar density.

positive unit jump when an electron is passed and a negative jump when a positron is passed. In this model, different vacua are represented by different quantized values of the electric field, while the electrons and positrons are the domain walls. This model is not fundamentally different from the case with scalar fields and a potential. In fact, by bosonizing the theory, it can be expressed as a scalar field theory with a potential:

$$V(\phi) = c\phi^2 + \mu \cos \phi. \quad (16.1)$$

If μ is not too small, there are many minima representing the different possible 2-form field strengths, each with a different energy.

In $3+1$ dimensions the corresponding construction requires a 4-form field strength F whose energy is also proportional to F^2 . This energy appears in the gravitational field equations as a positive contribution to the cosmological constant. The analogue of the charged electrons are membranes which appear in string theory and function as domain walls to separate vacua with different F . This theory can also be written in terms of a scalar field with a potential similar to Eq. (16.1). Henceforth I will include such fields, along with moduli, as coordinates of the landscape.

Let us now consider a typical compactification of M-theory from eleven to four dimensions. The simplest example is obtained by choosing for the compact directions a 7-torus. The torus has a number of moduli representing the sizes and angles between the seven 1-cycles. The 4-form fields have as their origin a 7-form field strength, which is one of the fundamental fields of M-theory.⁴ The 7-form fields have seven anti-symmetrized indices. These non-vanishing 7-forms can be configured so that three of the indices are identified with compact dimensions and the remainder are identified with uncompactified spacetime. This can be done in $(7 \times 6 \times 5)/(1 \times 2 \times 3) = 35$ ways, which means there are that many distinct 4-form fields in the uncompactified non-compact space. More generally, in the kinds of compact manifolds invoked in string theory to try to reproduce Standard Model physics, there can be hundreds of independent ways of ‘wrapping’ three compact directions with flux, thus producing hundreds of $3+1$ -dimensional 4-form fields. As in the case of $1+1$ -dimensional quantum electrodynamics, the field strengths are quantized, each in integer multiples of a basic field unit. A vacuum is specified by a set of integers $n_1, n_2, \dots, n_N$, where N can be as large as several hundred. The energy density of the 4-form fields has the

⁴ The fact that we have the number 7 appearing in two ways, as the number of compact dimensions and as the number of indices of the field strength, is accidental.

following form:

$$\epsilon = \sum_{i=1}^N c_i n_i^2, \quad (16.2)$$

where the constants c_i depend on the details of the compact space.

The analogue of the electrons and positrons of the $1+1$ -dimensional example are branes. The 11-dimensional M-theory has 5-branes which fill five spatial directions and time. By wrapping 5-branes the same way, the fluxes of the 4-forms are wrapped on internal 3-cycles, leaving 2-dimensional membranes in $3+1$ dimensions. These are the domain walls, which separate different values of field strength. There are N types of domain wall, each allowing a unit jump of one of the 4-forms.

Bousso and Polchinski [1] begin by assuming they have located some deep minimum of the field potential at some point Φ_0 . The value of the potential is supposed to be very negative at this point, corresponding to a negative cosmological constant, λ_0 , of order the Planck scale. Also the 4-forms are assumed to vanish at this point. They then ask what kind of vacua they can obtain by discretely increasing the 4-forms. The answer depends to some degree on the compactification radii of the internal space but – with modest parameters – it is not hard to get such a huge number of vacua that it is statistically likely to have one with cosmological constant $\lambda \sim 10^{-120} M_{\text{p}}^4$.

To see how this works, we write the cosmological constant as the sum of the cosmological constant for vanishing 4-form and the contribution of the 4-forms themselves:

$$\lambda = \lambda_0 + \sum_{i=1}^N c_i n_i^2. \quad (16.3)$$

With one hundred terms and modestly small values for the c_n , it is highly likely to find a value of λ in the observed range. Note that no fine-tuning is required, only a very large number of ways to make the vacuum energy. The problem with this proposal was clearly recognized by the authors [1]. The starting point is so far from the supermoduli-space that none of the usual tools of approximate supersymmetry are available to control the approximation. The example was intended only as a model of what might happen because of the large number of possibilities.

More recently, Kachru and colleagues [2] have improved the situation by finding an example which is more under control. These authors subtly use the various ingredients of string theory – including fluxes, branes, anti-branes and instantons – to construct a rather tractable example with a

small positive cosmological constant. In addition to arguing that string theory has many vacua with positive cosmological constant, the argument in ref. [2] tends to dispel the idea that vacua not on the supermoduli-space must have vanishing cosmological constant. In other words, there is no evidence in string theory that a hoped for – but unknown – mechanism will automatically force the cosmological constant to zero. It seems very likely that all of the non-supersymmetric vacua have finite λ .

The vacua in ref. [2] are not at all simple. They are jury-rigged Rubik–Goldberg contraptions that could hardly have fundamental significance. But in an anthropic theory, simplicity and elegance are not considerations. The only criterion for choosing a vacuum is utility, i.e. does it have the necessary elements, such as galaxy formation and complex chemistry, that are needed for life. That, together with a cosmology that guarantees a high probability that at least one large patch of space will form with that vacuum structure, is all we need.

16.2 The trouble with de Sitter space

The classical vacuum solution of Einstein’s equations with a positive cosmological constant is de Sitter space. It is doubtful that it has a precise meaning in a quantum theory such as string theory [4–6]. I want to review some of the reasons for thinking that de Sitter space is at best a meta-stable state.

It is important to recognize that there are two very different ways to think about de Sitter space. The first is to take a global view of the spacetime. The global geometry is described by the metric

$$ds^2 = R^2 \{ dt^2 - (\cosh t)^2 d^2\Omega_3 \}, \quad (16.4)$$

where $d^2\Omega_d$ is the metric for a unit d -sphere and R is related to the cosmological constant:

$$R = (\lambda G)^{-1/2}. \quad (16.5)$$

Viewing de Sitter space globally would make sense if it were a system that could be studied from the outside by a ‘meta-observer’. Naïvely, the meta-observer would make use of a (time-dependent) Hamiltonian to evolve the system from one time to another. An alternative description would use a Wheeler–De Witt formalism to define a wave-function of the Universe on global spacelike slices.

The other way of describing the space is the *causal patch* or ‘hot tin can’ description. The relevant metric is given by

$$ds^2 = R^2 \left\{ (1 - r^2) dt^2 - \frac{1}{(1 - r^2)} dr^2 - r^2 d^2\Omega_2 \right\}. \quad (16.6)$$

In this form, the metric is static and has a form similar to that of a black hole. In fact, the geometry has an horizon at $r = 1$. The static patch does not cover the entire global de Sitter space, but is analogous to the region outside a black hole horizon. It is the region which can receive signals from, and send signals to, an observer located at $r = 0$. To such an observer, de Sitter space appears to be a spherical cavity bounded by an horizon a finite distance away.

Experience with black holes has taught us to be very wary of global descriptions when horizons are involved. In a black hole geometry there is no global conventional quantum description of both sides of the horizon. This suggests that a conventional quantum description of de Sitter space only makes sense within a given observer’s causal patch. The descriptions in different causal patches are complementary [7, 8] but cannot be put together into a global description without somehow modifying the rules of quantum mechanics. As in the black hole case, an horizon implies a thermal behaviour with a temperature and an entropy. These are given by

$$T = \frac{1}{2\pi R}; \quad S = \frac{\pi R^2}{G}. \quad (16.7)$$

For the rest of this section, I will be assuming the causal patch description of some particular observer.

If the observed ‘dark energy’ in the Universe really is a small positive cosmological constant, the ultimate future of the Universe will be eternal de Sitter space. This would mean not that the future comprises totally empty space but that the world will have all the features of an isolated finite thermal cavity with finite temperature and entropy. Thermal equilibrium for such a system is not completely featureless. On short time-scales not much can be expected to happen, but on very long time-scales everything happens. A famous example involves a gas of molecules in a sealed room. Imagine that we start all the molecules in one corner of the room. In a relatively short time the gas will spread out to fill the room and come to thermal equilibrium. During the approach to equilibrium interesting dissipative structures, such as droplets, eddies and vortices, form and then dissipate. The usual assumption is that nothing happens after that. The entropy has reached its maximum value and the second law forbids any further interesting history.

But on a sufficiently long time-scale, large fluctuations will occur. In fact, the phase point will return over and over to the neighbourhood of any point in phase space, including the original starting point. These *Poincaré recurrences* generally occur on a time-scale with an exponential dependence on the thermal entropy of the system. Thus we define the Poincaré recurrence time to be

$$T_r = \exp S \quad (16.8)$$

in units of the Planck time. On such a long time-scale the second law of thermodynamics will repeatedly be violated by large-scale fluctuations. Thus, even a pure de Sitter space would have an interesting cosmology of sorts. The causal patch of any observer would undergo Poincaré recurrences in which it would endlessly fluctuate back to a state similar to its starting point, but each time it would be slightly different.

The trouble with such a cosmology is that it relies on very rare ‘miracles’ to start it off each time. But there are other miracles which could occur and lead to anthropically acceptable worlds with a vastly larger probability than our world. Roughly speaking, the relative probability of a fluctuation leading to a given configuration is proportional to the exponential of its entropy. An example of a configuration far more likely than our own would be a world in which everything was just like our universe except that the temperature of the cosmic microwave background was 10 K instead of 3 K. When I say ‘everything is the same’, I am including such details as the abundance of the elements.

Ordinarily such a universe would be ruled out on the grounds that it would take a huge miracle for the helium and deuterium to survive the bombardment by the extra photons implied by the higher temperature. That is correct, a fantastic miracle would be required, but such miracles would occur far more frequently than the ultimate miracle of returning to the starting point. This can be argued just from the fact that a universe at 10 K has a good deal more entropy than one at 3 K. In a world based on recurrences, it would be overwhelmingly unlikely that cosmology could be traced back to something like the inflationary era without a miraculous reversal of the second law along the way. Thus we are forced to conclude that the sealed ‘tin can’ model of the universe must be incorrect, at least for time-scales as long as the recurrence time.

Another difficulty with an eternal de Sitter space involves a mathematical conflict between the symmetry of de Sitter space and the finiteness of the entropy [4]. Basically, the argument is that the finiteness of the de Sitter space entropy indicates that the spectrum of energy is discrete. It is possible

to prove that the symmetry algebra of de Sitter space cannot be realized in a way that is consistent with the discreteness of this spectrum. In fact, this problem is not independent of the issues of recurrences. The discreteness of the spectrum means that there is a typical energy spacing of order

$$\Delta E \sim \exp(-S). \quad (16.9)$$

The discreteness of the spectrum can only manifest itself on time-scales of order $(\Delta E)^{-1}$, which is simply the recurrence time. Thus there are problems with realizing the full symmetries of de Sitter space for times as long as T_r .

Finally, another difficulty for eternal de Sitter space is that it does not fit at all well with string theory. Generally, the only objects in string theory which are rigorously defined are S-matrix elements. Such an S matrix cannot exist in a thermal background. Part of the problem is again the recurrences which undermine the existence of asymptotic states. Unfortunately, there are no known observables in de Sitter space which can substitute for S-matrix elements. The unavoidable implication of these issues is that eternal de Sitter space is an impossibility in a properly defined quantum theory of gravity.

16.3 de Sitter space is unstable

In ref. [2] a particular string theory vacuum with positive λ was studied. One of the many interesting things that the authors found was that the vacuum is unstable with respect to tunnelling to other vacua. In particular, the vacuum can tunnel back to the supermoduli-space with vanishing cosmological constant. Using instanton methods, the authors calculated that the lifetime of the vacuum is less than the Poincaré recurrence time. This is no accident. To see why it must always be so, let us consider the effective potential that the authors of ref. [2] derived. The only relevant modulus is the overall size of the compact manifold Φ . The potential is shown in Fig. 16.1. The de Sitter vacuum occurs at the point $\Phi = \Phi_0$. However, the absolute minimum of the potential occurs not at Φ_0 but at $\Phi = \infty$. At this point the vacuum energy is exactly zero and the vacuum is one of the 10-dimensional vacua of the supermoduli-space. As was noted long ago by Dine and Seiberg [9], there are always runaway solutions like this in string theory. The potential on the supermoduli-space is zero and so it is always possible to lower the energy by tunnelling to a point on the supermoduli-space.

Suppose we are stuck in the potential well at Φ_0 . The vacuum of the causal patch has a finite entropy and fluctuates up and down the walls of the potential. One might think that fluctuations up the sides of the potential are

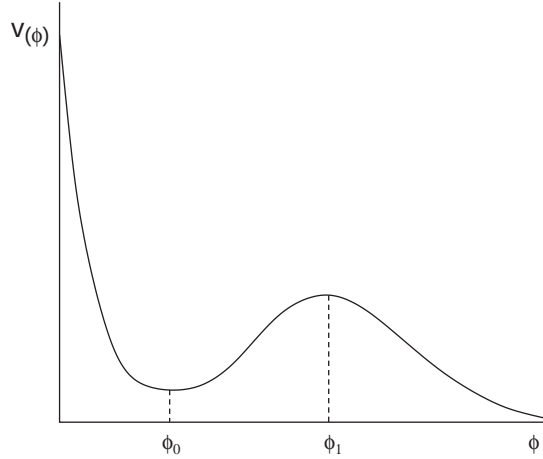


Fig. 16.1. The effective potential derived in ref. [2].

Boltzmann-suppressed. In a usual thermal system there are two things that suppress fluctuations. The first is the Boltzmann suppression by a factor $\exp(-\beta E)$ and the second is entropy suppression by a factor $\exp(S_f - S)$, where S is the thermal entropy and S_f is the entropy characterizing the fluctuation, which is generally smaller than S . However, in a gravitational theory in which space is bounded (as in the static patch), the total energy is always zero, at least classically. Hence the only suppression is entropic. The phase point wanders around in phase space, spending a time in each region proportional to its phase space volume, i.e. $\exp(-S_f)$. Furthermore the typical time-scale for such a fluctuation to take place is of order

$$T_f \sim \exp(S - S_f). \quad (16.10)$$

Now consider a fluctuation which brings the field ϕ to the top of the local maximum at $\phi = \phi_1$ in the entire causal patch. The entropy at the top of the potential is given in terms of the cosmological constant at the top. It is obviously positive and less than the entropy at ϕ_0 . Thus the time for the field to fluctuate to ϕ_1 (over the whole causal patch) is strictly less than the recurrence time $T_r = \exp S$. But once the field gets to the top, there is no obstruction to its rolling down the other side to infinity. It follows that a de Sitter vacuum of string theory is never longer lived than T_r and furthermore we end up at a supersymmetric point of vanishing cosmological constant.

There are other possibilities. If the cosmological constant is not very small, it may tunnel over the nearest mountain pass to a neighbouring valley

of smaller positive cosmological constant. This will also take place on a time-scale which is too short to allow recurrences. By the same argument, it will not stay in the new vacuum indefinitely. It may find a vacuum with yet smaller cosmological constant to tunnel to. Eventually it will have to make a transition out of the space of vacua with positive cosmological constant.⁵

16.4 Bubble cosmology

To make use of the enormous diversity of environments that string theory is likely to bring with it, we need a dynamical cosmology which, with high probability, will populate one or more regions of space with an anthropically favourable vacuum. There is a natural candidate for such a cosmology that I will explain from the global perspective.

For simplicity, let us temporarily assume that there are only two vacua: one with positive cosmological constant λ and the other with vanishing cosmological constant. Without worrying how it happened, we suppose that some region of the Universe has fallen into the minimum with positive cosmological constant. From the global perspective it is inflating and new Hubble volumes are constantly being produced by the expansion. Pick a timelike observer who looks around and sees a static region bounded by a horizon. The observer will eventually observe a transition in which the entire observable region slides over the mountain pass and settles into the region of vanishing λ . The observer sees the horizon-boundary quickly recede, leaving in its wake an infinite open Friedmann–Robertson–Walker (FRW) universe with negative spatial curvature. The final geometry has light-like and time-like future infinities similar to those in flat space.

It is helpful to draw some Penrose diagrams to illustrate the history. For this purpose we turn to the global point of view. Figure 16.2 shows the Penrose diagram for a pure de Sitter space. It also shows two observers whose causal patches overlap for some period of time. In Fig. 16.3 the same geometry is shown, except that the formation of a bubble of $\lambda = 0$ vacuum is also depicted. The bubble is created at point a and expands with a speed approaching that of light. Eventually the growing bubble intersects the infinite future of the de Sitter space but the geometry inside the bubble continues and forms a future null infinity. Note that even though the observer's final world is infinite, his past light-cone does not include the whole global

⁵ Tunnelling to vacua with negative cosmological constant may or may not be possible. However, such a transition will eventually lead to a crunch singularity. Whether the system survives the crunch is not known. It should be noted that transitions to negative cosmological constant are suppressed and can even be forbidden, depending on magnitudes of the vacuum energies and the domain wall tension. I will assume that such transitions do not occur.

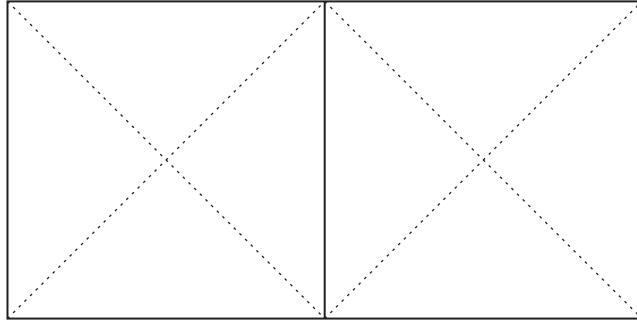
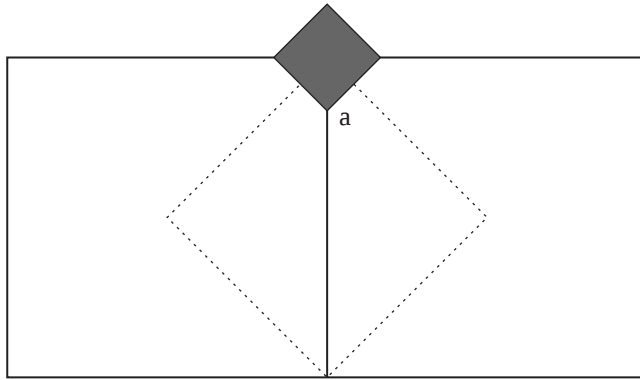


Fig. 16.2. Penrose diagram for pure de Sitter space.

Fig. 16.3. Penrose diagram for a $\lambda = 0$ bubble in de Sitter space.

spacetime. In fact, his causal diamond is not much bigger than it would have been if the space had never decayed. The region outside the bubble is still inflating and disappearing out of causal contact with the observer. From the causal patch viewpoint, the entire world has been swallowed by the bubble.

Now let us take the more global view. The bubble does not swallow the entire global space but leaves part of the space still inflating. Inevitably bubbles will form in this region. In fact, if we follow the worldline of any observer, it will eventually be swallowed by a bubble of $\lambda = 0$ vacuum. The line representing the remote future in Fig. 16.3 is replaced by a jagged fractal as in Fig. 16.4. Any observer eventually ends up at the top of the diagram in one of infinitely many time-like infinities. This process, leading to infinitely many disconnected bubble universes, is essentially similar to the process of eternal inflation envisioned by Linde [10].

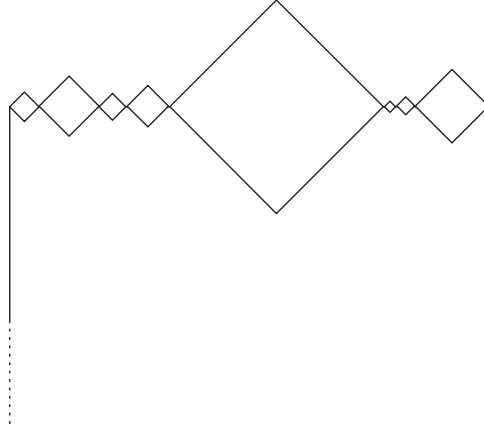


Fig. 16.4. Penrose diagram for many $\lambda = 0$ bubbles in de Sitter space

The real landscape does not comprise only two vacua. If an observer starts with a large value of the cosmological constant, there will be many ways for the causal patch to descend to the supermoduli-space. From the global viewpoint, bubbles will form in neighbouring valleys with somewhat smaller cosmological constant. Since each bubble has a positive cosmological constant, it will be inflating, but the space between bubbles is inflating faster, so the bubbles go out of causal contact with one another. Each bubble evolves in isolation from all the others. Furthermore, in a time too short for recurrences, bubbles will nucleate within bubbles. Following a single observer within his own causal patch, the cosmological constant decreases in a series of events until the causal patch finds itself in the supermoduli-space. Each observer will see a series of vacua descending to the supermoduli-space, and the chance that an observer passes through an anthropically acceptable vacuum is most likely very small. On the other hand, the global space contains an infinite number of such histories, and some of them will be acceptable.

The only problem with the above cosmology is that it is formulated in global coordinates. From the viewpoint of any causal patch, all but one of the bubbles is outside the horizon. As I have emphasized, the application of the ordinary rules of quantum mechanics only makes sense within the horizon of an observer. We do not know the rules for putting together the various patches into one comprehensive global description and, until we do, there cannot be any firm basis for this kind of anthropic cosmology. Nevertheless, the picture is tempting.

16.5 Cosmology as a resonance

The idea of scalar fields and potentials is approximate once we leave the supermoduli-space, as is the notion of a stable de Sitter vacuum. The problem is familiar. How do we make precise sense of an unstable state in quantum mechanics? In ordinary quantum mechanics the clearest situation is when we can think of the unstable state as a resonance in a set of scattering amplitudes. The parameters of a resonance, i.e. its width and mass, are well defined and do not depend on the exact way the resonance was formed. Thus, even black holes have precise meaning as resonant poles in the S-matrix. Normally we cannot compute the scattering amplitudes that describe the formation and evaporation of a black hole, but it is comforting that an exact criterion exists.

In the case of a black hole the density of levels is enormous, being proportional to the exponential of the entropy. The spacing between levels is therefore exponentially small. On the other hand, the width of each level is not very small. The lifetime of a state is the time it takes to emit a single quantum of radiation, and this is proportional to the Schwarzschild radius. Therefore the levels are broadened by much more than their spacing. The usual resonance formulae are not applicable, but the precise definition of the unstable state as a pole in the scattering amplitude is. I think the same things can be said about the unstable de Sitter vacua, but it can only be understood by returning to the ‘causal patch’ way of thinking. Therefore let us focus on the causal patch of one observer. We have discussed the observer’s future history and found that it always ends in an infinite expanding supersymmetric open FRW universe. Such a universe has the usual kind of asymptotic future, consisting of time-like and light-like infinities. There is no temperature in the remote future and the geometry permits particles to separate and propagate freely, just as in flat spacetime.

Now let us consider the observer’s past history. The same argument which says that the observer will eventually make a transition to $\lambda=0$ in the far future can be run backward. The observer could only have reached the de Sitter vacuum by the time-reversed history and so must have originated from a collapsing open universe. The entire history is shown in Fig. 16.5. The history may seem paradoxical, since it requires the second law of thermodynamics to be violated in the past. A similar paradox arises in a more familiar setting. Let us return to the sealed room filled with gas molecules, except that now one of the walls has a small hole that lets the gas escape to unbounded space. Suppose we find the gas filling the room in thermal equilibrium at some time. If we run the system forward, we will eventually

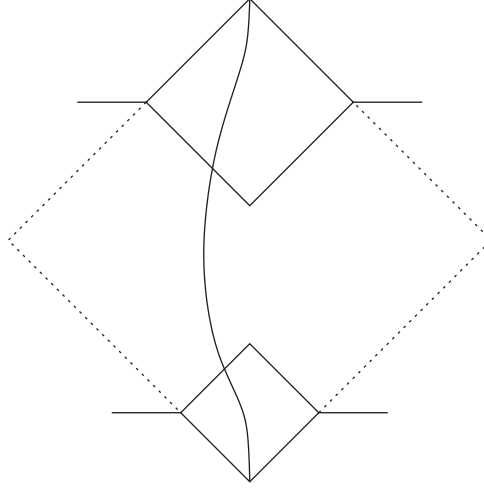


Fig. 16.5. de Sitter space as unstable resonance connecting asymptotic $\lambda = 0$ vacua.

find that all the molecules have escaped and are on their way out, never to return. But it is also true that, if we run the equations of motion backwards, we will eventually find all the molecules outside the room moving away. Thus the only way the starting configuration could have occurred is if the original molecules were converging from infinity toward the small hole in the wall.

If we are studying the system quantum mechanically, the metastable configuration with all the molecules in the room would be an unstable *resonance* in a scattering matrix describing the many-body scatterings of a system of molecules with the walls of the room. Indeed, the energy levels describing the molecules trapped inside the room are complex due to the finite lifetime of the configuration.

This suggests a view of the intermediate de Sitter space in Fig. 16.5 as an unstable resonance in the scattering matrix connecting states in the asymptotic $\lambda = 0$ vacua. In fact, we can estimate the width of the states. Since the lifetime of de Sitter space is always longer than the recurrence time, generally by a huge factor, the width γ satisfies $\gamma \gg \exp(-S)$. On the other hand, the spacing between levels, ΔE , is of order $\exp(-S)$. Therefore $\gamma \gg \Delta E$, so that the levels are very broad and overlapping, as for the black hole. No perfectly precise definition exists in string theory for the moduli fields or their potential when we go away from the supermoduli-space. The only precise definition of the de Sitter vacua seems to be as complex poles in some new sector of the scattering matrix between states on the supermoduli-space.

Knowing that a black hole is a resonance in a scattering amplitude does not tell us much about the way real black holes form. Most of the possibilities for black hole formation are just the time-reverse of the ways in which it evaporates. In other words, the overwhelming number of initial states that can lead to a black hole consist of thermal radiation. Real black holes in our universe form from stellar collapse, which is just one channel in a huge collection of S-matrix ‘in states’. In the same way, the fact that cosmological states may be thought of in a scattering framework does not itself shed much light on the original creation process.

16.6 Conclusion

Vacua come in two varieties: supersymmetric and non-supersymmetric. Most likely the latter do not have vanishing cosmological constant, but it is plausible that there are so many of them that they practically form a continuum. Some tiny fraction have a cosmological constant in the observed range. With nothing favouring one vacuum over another, the Anthropic Principle comes to the fore, whether or not we like the idea. String theory provides a framework in which this can be studied in a rigorous way. Progress can certainly be made in exploring the landscape. The project is in its infancy, but in time we should know just how rich it is. We can argue the philosophical merits of the Anthropic Principle, but we cannot argue with quantitative information about the number of vacua with each particular property, such as the cosmological constant, Higgs mass or fine structure constant. That information is there for us to extract.

Counting the vacua is important but not sufficient. A greater understanding of cosmological evolution is essential to determining if the large number of possibilities are realized as actualities. The vacua in string theory with $\lambda > 0$ are not stable and decay on a time-scale smaller than the recurrence time. This is very general and also very fortunate, since there are serious problems with stable de Sitter space. The instability also allows the Universe to sample all or a large part of the landscape by means of bubble formation. In such a world the probability that some region of space has suitable conditions for life to exist can be large.

The bubble universe based on Linde’s eternal inflation seems promising, but it is unclear how to think about it with precision. There are real conceptual problems having to do with the global view of spacetime. The main problem is to reconcile two pictures: the causal patch picture and the global picture. String theory has provided a testing ground for some important relevant ideas, such as black hole complementarity [7, 8] and the

Holographic Principle [11,12]. Complementarity requires the observer's side of the horizon to have a self-contained conventional quantum description. It also prohibits a conventional quantum description that covers the interior and exterior simultaneously. Any attempt to describe both sides as a single quantum system will come into conflict with one of three sacred principles [13]. The first is the Equivalence Principle, which says that a freely falling observer passes the horizon without incident. The second says that experiments performed outside a black hole should be consistent with the rules of quantum mechanics as set down in Dirac's textbook. No loss of quantum information should take place and the time evolution should be unitary. Finally, the rules of quantum mechanics forbid information duplication. This means that we cannot resolve the so-called information paradox by creating two copies (quantum xeroxing) of every bit as it falls through the horizon – at least not within the formalism of conventional quantum mechanics. The Complementarity and Holographic Principles have been convincingly confirmed by the modern methods of string theory (see, for example, ref. [14]). The inevitable conclusion is that a global description of geometries with horizons, if it exists at all, will not be based on the standard quantum rules.

Why is this important for cosmology? The point is that the eternal inflationary production of an infinity of bubbles takes place behind the horizon of any given observer. It is not something that has a description within one causal patch. If it makes sense, a global description is needed. However, if cosmic event horizons are at all like black hole horizons, then any global description will involve wholly new elements. If I were to make a wild guess about which rule of quantum mechanics has to be given up in a global description of either black holes or cosmology, I would guess it is the Quantum Xerox Principle [13]. I would look for a theory which formally allows quantum duplication but cleverly prevents any observer from witnessing it. Perhaps then the replication of bubbles can be sensibly described.

Progress may also be possible in sharpening the exact mathematical meaning of the de Sitter vacua. Away from the supermoduli-space, the concept of a local field and the effective potential is at best approximate in string theory. The fact that the vacua are false meta-stable states makes it even more problematic to be precise. In ordinary quantum mechanics the best mathematical definition of an unstable state is as a resonance in the amplitude for scattering between very precisely defined asymptotic states. Each meta-stable state corresponds to a pole whose real and imaginary parts define the energy and inverse lifetime of the state.

I have argued that each causal patch begins and ends with an asymptotic ‘roll’ toward the supermoduli-space. The final states have the boundary conditions of an FRW open universe and the initial states are time-reversals of these. This means we may be able to define some kind of S-matrix connecting initial and final asymptotic states. The various intermediate meta-stable de Sitter phases would be exactly defined as resonances in this amplitude.

At first this proposal sounds foolish. In General Relativity, initial and final states are very different. Black holes make sense. White holes do not. Ordinary things fall into black holes and thermal radiation comes out. The opposite never happens. But this is deceptive. Our experience with string theory has made it clear that the fundamental microphysical input is completely reversible and that black holes are most rigorously defined in terms of resonances in scattering amplitudes.⁶ Of course, knowing that a black hole is an intermediate state in a tremendously complicated scattering amplitude does not really tell us much about how real black holes form. For that, we need to know about stellar collapse and the like. But it does provide an exact mathematical definition of the states that comprise the black hole ensemble.

To further illustrate the point, let me tell a story. Two future astronauts in the deep empty reaches of outer space discover a sealed capsule. On further inspection, they find a tiny pinhole in the capsule from which air is slowly leaking out. One says to the other, ‘Aha! We have discovered an eternal air tank. It must have been here forever.’ The other says, ‘No, you fool. If it were here forever, the air would have leaked out an infinitely long time ago.’ So, the first one thinks and says, ‘Yes, you are right. Let’s think. If we wait long enough, all the air will be streaming outward in an asymptotic final state. That is clear. But because of microreversibility, it is equally clear that – if we go far into the past – all the air must have been doing the reverse. In fact, the quantum states with air in the capsule are just intermediate resonances in the scattering of a collection of air molecules with the empty capsule.’ The second astronaut looks at the first as if he were nuts. ‘Don’t be a dope,’ he says. ‘That’s just too unlikely. I guess someone else was here not so long ago and filled it up.’

Both of them can be right. The quantum states of air in a tank are mathematical resonances in a scattering matrix. And it may also be true that the laws of an isolated system of gas and tank may have been temporarily interfered with by another presence. Or we might say that the scattering

⁶ The one exception is a black hole in anti-de Sitter space, which is stable.

states need to include not only air and tank but also astronauts and their apparatus. It is in this sense that I propose that de Sitter space can be mathematically defined in terms of singularities in some kind of generalized S matrix. But in so doing, I am not really telling you much about how it all started.

From the causal patch view-point, the evolutionary endpoint seems to be an approach to some point on the supermoduli-space. After the last tunnelling, the Universe enters a final open FRW expansion toward some flat supersymmetric solution. This is not to be thought of as a unique quantum state but as a large set of states with similar evolution. Running the argument backward (assuming microscopic reversibility), we expect the initial state to be the time-reversal of one of the many future endpoints. We might even hope for a scattering matrix connecting initial and final states. de Sitter minima would be an enormously large density of complex poles in the amplitude.

One last point: the final and initial states do not have to be 4-dimensional. In fact, in the example given in ref. [2], the modulus describing the overall size of the compact space rolls to infinity, thus creating a 10- or possibly 11-dimensional universe.

Acknowledgements

I am indebted to Simeon Hellerman, Ben Freivogel, Renata Kallosh, Shamit Kachru, Eva Silverstein and Steve Shenker. Special thanks go to Matt Kleban and Andrei Linde for explaining many things to me.

References

- [1] R. Bousso and J. Polchinski. Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. *JHEP*, **0006** (2000), 006 [hep-th/0004134].
- [2] S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi. de Sitter vacua in string theory. *Phys. Rev. D* **68** (2003), 046005 [hep-th/0301240].
- [3] J. D. Brown and C. Teitelboim. Neutralization of the cosmological constant by membrane creation. *Nucl. Phys. B* **297** (1988), 787.
- [4] N. Goheer, M. Kleban and L. Susskind. The trouble with de Sitter space. *JHEP* **0307** (2003), 056 [hep-th/0212209].
- [5] L. Dyson, J. Lindesay and L. Susskind. Is there really a de Sitter/CFT duality? *JHEP* **0208** (2002), 045 [hep-th/0202163].
- [6] L. Dyson, M. Kleban and L. Susskind. Disturbing implications of a cosmological constant. *JHEP*, **0210** (2002), 011 [hep-th/0208013].
- [7] L. Susskind, L. Thorlacius and J. Uglum. The stretched horizon and black hole complementarity. *Phys. Rev. D* **48** (1993), 3743 [hep-th/9306069].

- [8] C. R. Stephens, G. 't Hooft and B. F. Whiting. Black hole evaporation without information loss. *Class. Quant. Grav.* **11** (1994), 621 [gr-qc/9310006].
- [9] M. Dine and N. Seiberg. Comments on higher derivative operators in some SUSY field theories. *Phys. Lett.* **B 409** (1997), 239.
- [10] A. D. Linde. Eternally existing self-reproducing chaotic inflationary universe. *Phys. Lett.* **B 175** (1986), 395.
- [11] G. 't Hooft. Dimensional reduction in quantum gravity. In *Salamfest 1993* (1993), pp. 284–96 [gr-qc/9310026].
- [12] L. Susskind. The world as a hologram. *J. Math. Phys.* **36** (1995), 6377 [hep-th/9409089].
- [13] L. Susskind. Twenty years of debate with Stephen. In *The Future of Theoretical Physics*, eds. G. W. Gibbons, E. P. S. Shellard and S. J. Ranken (Cambridge: Cambridge University Press, 2003), pp. 330–47 [hep-th/0204027].
- [14] J. M. Maldacena. Eternal black holes in AdS. *JHEP*, **0304** (2001), 021 [hep-th/0106112].

17

Cosmology and the many worlds interpretation of quantum mechanics

V. F. Mukhanov

Sektion Physik, Ludwig-Maximilians-Universität

17.1 Introduction

Although the mathematical structure of quantum mechanics was understood within a few years after it was invented, numerous quantum paradoxes still disturb ‘simple-minded’ physicists. Most of them, as ‘naïve realists’, would probably never take Bohr’s own over-philosophical and over-complicated treatment of these paradoxes seriously if they realized the philosophical consequences of the Copenhagen interpretation. To make my meaning clearer, let me quote Bohr’s answer to Professor Hoffding’s question regarding the double-slit experiment [1]. Bohr was asked: ‘What can the electron be said to *be* in its travel from the point of entry to the point of detection?’ And he replied: ‘*To be? To be? What does it mean to be?*’ However, if one questions the existence of microscopic constituents of macroscopic bodies, then the next logical step would be to question the existence of the macroscopic bodies and even ourselves.

Needless to say, very few (if any) of us, when making experiments or analyzing their results, address the question of what it means ‘to be’ every time. Even in the context of elementary particles, probably nobody doubts that the particles exist and somehow travel from the point of entry to the point of detection. Moreover, within the accuracy allowed by the uncertainty relation, these particles can be localized and described just as well as macroscopic ‘classical’ objects.

If this intuitive point of view is correct, then everything is in perfect agreement with what we used to think about the world existing ‘out there’ and independently of us. Our feeling is that this world can be well described by physical laws which (within a limited accuracy) are in ‘one-to-one correspondence’ with reality.

Universe or Multiverse?, ed. Bernard Carr. Published by Cambridge University Press.
© Cambridge University Press 2007.

However, this is not what Bohr's interpretation of quantum mechanics tells us. According to Bohr, '... any talk about what the photon is doing between the point of production and the point of reception is ... simply mere talk' [1]. The observer becomes an active 'player in the game', and the physical laws just serve the observer's needs, simply relating the outcomes of the measurements without addressing the question of what the world looks like 'out there'. In this case, quantum mechanics does not make much sense in the absence of observers.

17.2 The Copenhagen picture

In fact, Bohr's interpretation is more than just an interpretation of the equations of quantum mechanics. It puts limits on the applicability of these equations and, at some point, replaces the unitary evolution by a mysterious collapse of the wave-function. One has to stress that this collapse is not derivable – even in principle – from the equations of quantum mechanics. There is no definite quantitative answer as to when the collapse should take place. One usually says that the reduction of the wave-function happens at some point during the interaction of the quantum system with the measuring device. This interaction point can be moved arbitrarily unless it is possible to observe the interference of the 'classically described' macroscopic objects [2]. (Observing the interference is an incredibly difficult enterprise for macroscopic objects because of decoherence.) The 'size of the object' is not a good criterion for telling us when the Schrödinger equation should be replaced by 'classical laws'.

This last statement immediately provokes the question: should not the classical equations just follow from quantum mechanical equations in the limit when the Planck constant $\hbar$ goes to zero, or equivalently when we apply quantum mechanics to macroscopic objects? There are good reasons to believe that this should be the case. In fact, quantum theory is usually constructed by replacing numbers in classical equations by operators which have to satisfy appropriate commutation relations to fulfil the uncertainty relations. In the limit $\hbar \rightarrow 0$, all these operators should commute and one could anticipate that the expectation values of operators should satisfy the classical equations to within an accuracy proportional to $\hbar$. However, this is not the case for all admissible quantum states, even if the objects under consideration are macroscopic ('classical'). If one assumes that a macroscopic system can be well described by quantum mechanics, then its generic quantum state is a superposition of various macroscopically different states.

The most famous example of such a state is Schrödinger's cat. It is clear that any operator characterizing the state of the cat produces a nonsensical result if the operator is being averaged over a superposition of 'the dead and alive cat'. If we describe measurements using the quantum mechanical equations, then again the final state of the apparatus is generically a superposition of macroscopically different states. This superposition is a complete analogue of the 'Schrödinger cat' one. The macroscopic superpositions occur commonly if one universally applies the Schrödinger equation. After amplification, the microscopical superpositions generically evolve into quantum states, which, if naïvely 'mapped onto reality', should correspond to 'schizophrenic states' of macroscopic objects. Nobody has ever observed such states. I would like to stress here that the classical limit for the superposition of macroscopic states does not exist even when the Planck constant $\hbar$ goes to zero. Once created, these states survive in the limit $\hbar \rightarrow 0$.

Bohr changed the rules of quantum mechanics and put bounds on the applicability of the Schrödinger equation. The reduction postulate introduced by Bohr was mainly needed to get rid of macroscopic superpositions. At first glance, it looks like a simple modification of the equations of motion without far-reaching philosophical consequences. However, these consequences are much deeper than one could expect. For the reduction postulate forces us to change the old classical concept of reality. I do not mean here the rather trivial point that, due to the uncertainty principle, particles in quantum mechanics have no trajectories, or the less trivial point expressed by Einstein as 'God playing dice'. To make the interpretation at least *look* self-consistent, one has to abandon the notion of reality as most of us (even many of those who claim that they agree with Bohr's interpretation) used to understand it. One has to accept that physics does not describe the world 'out there' and its purpose is only to bring some order to our perceptions of the world. The observer (or a 'classical device', as some prefer to say) becomes an inevitable ingredient of any physical theory, playing a central role in the interpretation of the outcome of the equations.

This leads to a complicated philosophical scheme, known as the Copenhagen interpretation, which goes far beyond the 'practical' reduction postulate and statistical interpretation of the wave-function. This scheme is so confusing that it would probably be fair to say that there are many different interpretations of the Copenhagen interpretation. Things become even more dramatic when one applies quantum theory to the Universe. Then the logical implementation of the Copenhagen philosophy looks like a joke.

17.3 Everett's picture

Is there any alternative to the Copenhagen interpretation which would allow us to return to the 'old classical scheme' (perhaps in a modified form)? The answer to this question was given by Everett thirty years after quantum mechanics was invented. This answer is simple but non-trivial. To obtain it, one just has to *interpret* what quantum mechanics really tells us without trying to change its rules to suit our prejudice. As a first step, one has to admit the existence of macroscopic superpositions as a reality. Then how can this be reconciled with the fact that the macroscopic objects we observe are not in 'schizophrenic' states? The only way to avoid a contradiction is to take the next step and admit that quantum mechanics actually always describes an ensemble of many *real universes*. Therefore the discovery of quantum mechanics was in fact the discovery which gave a solid scientific basis to the 'Multiverse versus Universe' debate.

In Everett's interpretation, the different superpositions of the macroscopic states correspond to different ensembles of the universes which they describe. We are back to the 'classical idea' of a one-to-one correspondence between reality and the mathematical symbols which are used to describe it. We also return to the idea that physics describes not only 'our knowledge and perceptions' but also the world 'out there', which *existed* and *will exist* without any observers. However, it is not a single world anymore – instead it is many universes. If we admit this, we also have to accept the 'crazy consequence', namely, the existence of many copies of ourselves which are as real as we are. This is the 'price' one has to pay for the *interpretation* of the theory as it is and for the simple resolution of quantum paradoxes. Since there is nothing wrong any more with the universality of quantum theory, it can be also applied to the whole Universe. Measurements can be completely described by quantum equations and the statistical interpretation can be derived within quantum mechanics (i.e. it does not need to be postulated separately) [3, 4].

According to Everett's interpretation, classical mechanics can always be derived as a limiting case of quantum theory ($\hbar \rightarrow 0$). One just needs to expand the wave-function in a preferable basis and then identify the various components of this basis with different quasi-classical universes. In turn, the preferable basis is determined by the requirement that the appropriate expectation values of the 'macroscopic operators' for the state vectors of this basis satisfy the classical equations of motion [5]. The quasi-classical corrections to the equations are proportional to the Planck constant. These corrections characterize 'the strength of quantum interactions' (interference)

of different universes. Of course, due to decoherence, two very different universes ‘interact’ very little and it is *practically impossible* to verify their existence. However, ‘practically impossible’ does not mean *impossible in principle*. For instance, the existence of our copies in other universes, which at present strongly decohere with ‘us’, would influence ‘our future’ on a Poincaré timescale. And if something can *in principle* influence our reality, then it means that this something is as real as ‘our reality’. The universes which are just different at microscopic level ‘communicate’ (interfere) too strongly to speak about well defined ‘different’ universes. In this case the ‘multiverse’ becomes a more complex concept. Nevertheless, the existence of this multiverse allows us to understand the interference phenomena.

17.4 Quantum cosmology

Let me turn now to quantum cosmology. According to inflationary models, the primordial inhomogeneities responsible for the large-scale structure originated from the initial vacuum fluctuations, amplified during a stage of accelerated expansion [6]. The initial (vacuum) state of the quantum fluctuations is translationally invariant (i.e. there are no preferred points), and the quantum state remains translationally invariant as the fluctuations are excited. How, in this case, can one understand the fact that the translational invariance is finally broken and that we observe galaxies in certain locations on the sky? One could ask, for instance, why our galaxy is located in the particular place where we observe it and not a few Mpc away. What determined the choice of this place?

If one considers the wave-functional describing the perturbations, then this functional remains translationally invariant even after the occupation numbers in every mode have grown tremendously. After inflation, this wave-functional is a superposition of different components, each one corresponding to macroscopically different universes. One of these universes looks like the one we observe today. In another one, the ‘galaxy’ similar to our own is shifted to a position 10 Mpc away, and so on. Every ‘non-schizophrenic’ component of the wave-function describes a state with broken translational invariance. However, their sum remains translationally invariant. If one assumes that the Schrödinger equation is universal and applies it also to observers, then nobody can make a selection of a particular ‘real’ component from the superposition. Therefore all terms in this superposition come with the ‘same rights of existence’. Since we know that one of the components surely corresponds to the reality describing our world, we have

to admit that the others also correspond to some reality. Thus we arrive at an ensemble of many *real*, classically different universes, with statistical properties characterized by the correlation functions which can be calculated as usual.

The situation with the wave-function of the whole Universe is very similar. The natural boundary conditions for the wave-function of the Universe [7] always predict states which are superpositions of macroscopically different universes. These universes are highly decoherent, do not interfere with each other, and differ even more than in the case of cosmological perturbations. The wave-function localized near a particular classical trajectory can in principle also be constructed, but only as a result of substantial effort and it does not look very natural. According to Everett's interpretation, all universes are real. One could expect that a theory of quantum gravity will finally allow us to introduce a natural measure to characterize how frequently a universe of a certain type occurs in the ensemble. It is very likely that, according to this (as yet unknown) measure, the ratio of the number of 'big universes' to the number of 'small universes' in the ensemble will be much larger for models with an inflationary stage than for models without such a stage. If the measure is ever constructed, it will allow us to put the statement that 'inflation solves the problem of initial conditions' on a solid mathematical ground. At present, this statement is justified only by our feeling and intuition.

17.5 Conclusions

Probably the main reason why Everett's interpretation has not been taken very seriously by the scientific community up to now is because it predicts the reality of our 'copies'. On the other hand, as we know, the theory of inflation leads to a picture of an eternal self-reproducing universe. It is clear that, in such a universe, one can always find an unlimited number of worlds which are very similar to our world and filled by our copies. Unlike 'quantum copies', these 'eternal universe copies' are less dangerous and more useless, since they will never communicate with us. However, if we seriously believe this picture, then the most important psychological reason to reject the Everett interpretation is gone. Since the 'many worlds' interpretation is the *only* logical interpretation of quantum mechanics, I do not see any reason to substitute it with a 'many *words* interpretation' merely to suit our prejudice. Everett's interpretation is crazy enough to be true, and therefore surely deserves very serious attention.

References

- [1] J. A. Wheeler. In *Physical Origins of Time Asymmetry*, eds. J. J. Halliwell, J. Perez-Mercader and W. H. Zurek (Cambridge: Cambridge University Press, 1994), p. 1.
- [2] J. von Neumann. In *Mathematical Foundations of Quantum Mechanics* (Princeton: Princeton University Press, 1955).
- [3] H. Everett. *Rev. Mod. Phys.* **29** (1957), 454.
- [4] H. Everett. In *The Many-Worlds Interpretation of Quantum Mechanics*, eds. B. S. DeWitt and N. Graham (Princeton: Princeton University Press, 1973), p. 3.
- [5] V. Mukhanov. *Phys. Lett.* **127A** (1988), 251.
- [6] V. Mukhanov and G. Chibisov. *JETP Lett.* **33** (1981), 533.
- [7] J. B. Hartle and S. W. Hawking. *Phys. Rev.* **B 28** (1983), 2620.
- [8] A. Linde. *Lett. Nuovo Cim.* **39** (1984), 401.
- [9] A. Vilenkin. *Phys. Rev.* **D 30** (1984), 509.

Anthropic reasoning and quantum cosmology¹

James B. Hartle

Department of Physics, University of California, Santa Barbara

18.1 Introduction

If the Universe is a quantum mechanical system, then it has a quantum state. This state provides the initial condition for cosmology. A theory of this state is an essential part of any final theory summarizing the regularities exhibited universally by all physical systems and is the objective of the subject of quantum cosmology. This chapter is concerned with the role that the state of the Universe plays in anthropic reasoning – the process of explaining features of the Universe from our existence in it [1]. The thesis will be that anthropic reasoning in a quantum mechanical context depends crucially on assumptions about the Universe’s quantum state.

18.2 A model quantum Universe

Every prediction in a quantum mechanical Universe depends on its state, if only very weakly. Quantum mechanics predicts probabilities for alternative possibilities, most generally the probabilities for alternative histories of the Universe. The computation of these probabilities requires both a theory of the quantum state as well as the theory of the dynamics specifying its evolution.

To make this idea concrete while keeping the discussion manageable, we consider a model quantum Universe. The details of this model are not essential to the subsequent discussion of anthropic reasoning but help to fix the notation for probabilities and provide a specific example of what they mean. Particles and fields move in a large – perhaps expanding – box, say, presently 20 000 Mpc on a side. Quantum gravity is neglected – an excellent

¹ This is a reworking of an article, reproduced with permission, from *The New Cosmology: Proceedings of the Conference on Strings and Cosmology*, eds. R. Allen, D. Nanopoulos and C. Pope, AIP Conference Proceedings 743 (New York: American Institute of Physics, 2004).

approximation for accessible alternatives in our Universe later than 10^{-43} s after the big bang. Spacetime geometry is thus fixed with a well defined notion of time, and the usual quantum apparatus of Hilbert space states and their unitary evolution governed by a Hamiltonian can be applied.²

The Hamiltonian H and the state $|\Psi\rangle$ in the Heisenberg picture are the assumed theoretical inputs to the prediction of quantum mechanical probabilities. Alternative possibilities at one moment of time t can be reduced to yes/no alternatives represented by an exhaustive set of orthogonal projection operators $\{P_\alpha(t)\}$ ($\alpha=1,2,\dots$) in this Heisenberg picture. The operators representing the same alternatives at different times are connected by:

$$P_\alpha(t) = e^{iHt/\hbar} P_\alpha(0) e^{-iHt/\hbar}. \quad (18.1)$$

For instance, the P s could be projections onto an exhaustive set of exclusive ranges of the centre-of-mass position of the Earth, labelled by α . The probabilities $p(\alpha)$ that the Earth is located in one or another of these regions at time t is given by

$$p(\alpha|H, \Psi) = \|P_\alpha(t) |\Psi\rangle\|^2. \quad (18.2)$$

The probabilities for the Earth's location at a different time is given by the same formula with different P s computed from the Hamiltonian by Eq. (18.1). The notation $p(\alpha|H, \Psi)$ departs from usual conventions (e.g. ref. [2]) to indicate explicitly that all probabilities are conditioned on the theory of the Hamiltonian H and quantum state $|\Psi\rangle$.

Most generally, quantum theory predicts the probabilities of sequences of alternatives at a series of times – that is *histories*. An example is a sequence of ranges of centre-of-mass position of the Earth at a series of times giving a coarse-grained description of its orbit. Sequences of sets of alternatives $\{P_{\alpha_k}^k(t_k)\}$ at a series of times t_k ($k=1,\dots,n$) specify a set of alternative histories of the model. An individual history α in the set corresponds to a particular sequence of alternatives $\alpha \equiv (\alpha_1, \alpha_2, \dots, \alpha_n)$ and is represented by the corresponding chain of projection operators C_α :

$$C_\alpha \equiv P_{\alpha_n}^n(t_n) \cdots P_{\alpha_1}^1(t_1), \quad \alpha \equiv (\alpha_1, \dots, \alpha_n). \quad (18.3)$$

The probabilities of the histories in the set are given by

$$p(\alpha|H, \Psi) \equiv p(\alpha_n, \dots, \alpha_1|H, \Psi) = \|C_\alpha |\Psi\rangle\|^2 \quad (18.4)$$

² For a more detailed discussion of this model in the notation used here, see ref. [2]. For a quantum framework when spacetime geometry is not fixed, see, e.g., ref. [3].

provided the set decoheres, i.e. provided the branch state vectors $C_\alpha|\Psi\rangle$ are mutually orthogonal. Decoherence ensures the consistency of the probabilities given by Eq. (18.4) with the usual rules of probability theory.³

To use either Eq. (18.2) or (18.4) to make predictions, a theory of *both* H and $|\Psi\rangle$ is needed. No state means no predictions.

18.3 What is predicted?

‘If you know the wave-function of the Universe, why aren’t you rich?’ This question was once put to me by my colleague Murray Gell-Mann. The answer is that there are unlikely to be any alternatives relevant to making money that are predicted as sure bets, conditioned just on the Hamiltonian and quantum state alone. A probability $p(\text{rise}|H, \Psi)$ for the stock market to rise tomorrow could be predicted from H and $|\Psi\rangle$ through Eq. (18.2) in principle. But it seems likely that the result would be a useless $p(\text{rise}|H, \Psi) \approx 1/2$, conditioned just on the ‘no boundary’ wave-function [7] and M-theory.

It is plausible that this is the generic situation. To be manageable and discoverable, the theories of dynamics and the quantum state must be short – describable in terms of a few fundamental equations and the explanations of the symbols they contain. It is therefore unlikely that H and $|\Psi\rangle$ contain enough information to determine most of the interesting complexity of the present Universe with significant probability [8, 9]. We *hope* that the Hamiltonian and quantum state are sufficient conditions to predict certain large-scale features of the Universe with significant probability. Approximately classical spacetime, the number of large spatial dimensions, the approximate homogeneity and isotropy on scales above several hundred Mpc, and the spectrum of density fluctuations that were the input to inflation are some examples of these. But even a simple feature, such as the time the Sun will rise tomorrow, will not be usefully predicted by our present theories of dynamics and the quantum state *alone*.

The time of sunrise *does* become predictable with high probability if a few previous positions and orientations of the Earth in its orbit are supplied in addition to H and $|\Psi\rangle$. That is a particular case of a *conditional probability* of the form

$$p(\alpha|\beta, H, \Psi) = \frac{p(\alpha, \beta|H, \Psi)}{p(\beta|H, \Psi)} \quad (18.5)$$

³ For a short introduction to decoherence, see ref. [2] or any of the classic expositions of decoherent (consistent) histories quantum theory [4–6].

for alternatives α (e.g. the times of sunrise), given H and $|\Psi\rangle$ and further alternatives β (e.g. a few earlier positions and orientations of the Earth). The joint probabilities on the right-hand-side of Eq. (18.5) are computed using Eq. (18.4), as described in Section 18.2.

Conditioning probabilities on specific information can weaken their dependence on H and $|\Psi\rangle$ but does not eliminate it. That is because any specific information available to us as human observers (such as a few positions of the Earth) is but a small part of that needed to specify the state of the Universe. The chains of the form given in Eqs. (18.3) that define a few previous positions of the Earth in Eqs. (18.4) and (18.5) involve projections P_γ that define a previous position to a certain accuracy. These span a very large subspace of the Hilbert space, so that $P_\gamma|\Psi\rangle$ depends strongly on $|\Psi\rangle$. For example, to extrapolate present data on the Earth to its position 24 hours from now requires that the probability be high that it moves on a classical orbit in that time and that the probability be low that it is destroyed by a neutron star now racing across the Galaxy at near light speed. Both of these probabilities depend crucially on the nature of the quantum state [10].

Many useful predictions in physics are of conditional probabilities of the kind discussed in this section. We next turn to the question of whether we should be part of the conditions.

18.4 Anthropic reasoning – less is more

18.4.1 Anthropic probabilities

In calculating the conditional probabilities for predicting some of *our* observations given others, there can be no objection of principle to including a description of ‘us’ as part of the conditions:

$$p(\alpha|\beta, \text{‘us’}, H, \Psi). \quad (18.6)$$

Drawing inferences using such probabilities is called *anthropic reasoning*. The motivation is the idea that probabilities for certain features of the Universe might be sensitive to this inclusion.

The utility of anthropic reasoning depends on how sensitive probabilities like Eq. (18.6) are to the inclusion of ‘us’. To make this concrete, consider the probabilities for a hypothetical cosmological parameter we will call Λ . We will assume that H and $|\Psi\rangle$ imply that Λ is constant over the visible Universe, but only supply probabilities for the various constant values it might take through Eq. (18.4). We seek to compare $p(\Lambda|H, \Psi)$ with $p(\Lambda|\text{‘us’}, H, \Psi)$. In principle, *both* are calculable from Eqs. (18.4) and (18.5). Figure 18.1 shows three possible ways in which they might be related.

- $p(\Lambda|H, \Psi)$ is peaked around one value, as in Fig. 18.1(a). The parameter Λ is determined either by H or $|\Psi\rangle$ or by both.⁴ Anthropic reasoning is not necessary; the parameter is already determined by fundamental physics.
- $p(\Lambda|H, \Psi)$ is distributed and $p(\Lambda|‘us’, H, \Psi)$ is also distributed, as in Fig. 18.1(b). Anthropic reasoning is inconclusive. One might as well measure the value of Λ and use this as a condition for making further predictions,⁵ i.e. work with probabilities of the form $p(\alpha|\Lambda, H, \Psi)$.
- $p(\Lambda|H, \Psi)$ is distributed but $p(\Lambda|‘us’, H, \Psi)$ is peaked, as in Fig. 18.1(c). Anthropic reasoning helps to explain the value of Λ .

The important point to emphasize is that a *theoretical hypothesis for H and $|\Psi\rangle$ is needed to carry out anthropic reasoning*. Put differently, a theoretical context is needed to decide whether a parameter like Λ *can* vary, and to find out *how* it varies, before using anthropic reasoning to restrict its range. The Hamiltonian and quantum state provide this context. In Section 18.5, we will consider the situation where the state is imperfectly known.

18.4.2 Less is more

While there can be no objections in principle to including ‘us’ as a condition for the probabilities of our observations, there are formidable obstacles in practice.

- We are complex physical systems requiring an extensive environment and a long evolutionary history, whose description in terms of the fundamental variables of H and $|\Psi\rangle$ may be uncertain, long and complicated.
- The complexity of the description of a condition including ‘us’ may make the calculation of the probabilities long or impossible as a practical matter.

In practice, therefore, the anthropic probabilities given by Eq. (18.6) can only be estimated or guessed. Theoretical uncertainty in the results is thereby introduced.

The objectivity striven for in physics consists, at least in part, in using probabilities that are not too sensitive to ‘us’. We would not have science if anthropic probabilities for observation depended significantly on which individual human being was part of the conditions. The existence of schizophrenic delusions shows that this is possible, so that the notion of ‘us’ should be restricted to exclude such cases.

⁴ As, for example, in the as yet inconclusive discussions of baby Universes [11,12].

⁵ As stressed by Hawking and Hertog [13].

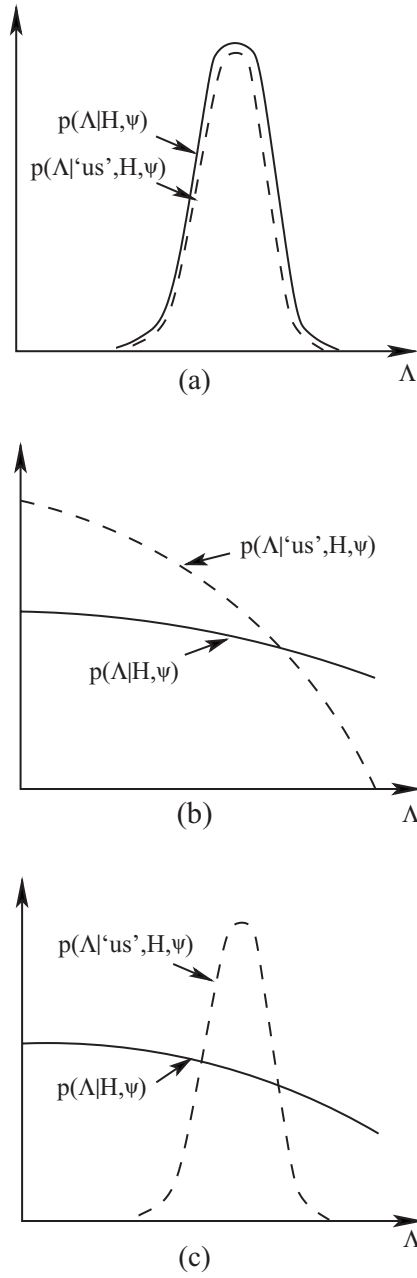


Fig. 18.1. Some possible behaviours for probabilities for the value of a cosmological parameter Λ with and without the condition 'us'. (a) The value of Λ is fixed by H and $|\Psi\rangle$, so anthropic reasoning is not needed. (b) Anthropic probabilities are distributed, so anthropic reasoning is useless in fixing Λ . (c) Anthropic reasoning is useful.

For these reasons, it is prudent to condition probabilities, not on a detailed description of ‘us’, but on the weakest condition consistent with ‘us’ that plausibly provides useful results such as those illustrated in Fig. 18.1(c). A short list of conditions of roughly decreasing complexity might include:

- human beings;
- carbon-based life;
- information gathering and utilizing systems;
- at least one galaxy;
- a Universe older than 5 Gy;
- no condition at all.

For example, the probabilities used to bound the cosmological constant Λ make use of the fourth and fifth items on this list, under the assumption that including earlier ones will not greatly affect the anthropically allowed range for Λ [1]. (For recent reviews with references to earlier literature, see refs. [14] and [15].) To move down in the above list of conditions is to move in the direction of increasing theoretical certainty and decreasing computational complexity. With anthropic reasoning, less is more.

18.5 Ignorance is *not* bliss

The quantum state of a single isolated subsystem generally cannot be determined from a measurement carried out on it. That is because the outcomes of measurements are distributed probabilistically and the outcome of a single trial does not determine the distribution. Neither can the state be determined from a series of measurements, because measurements disturb the state of the subsystem. The Hamiltonian cannot be inferred from a sequence of measurements on one subsystem for similar reasons. In the same way, we cannot generally determine either the Hamiltonian or the quantum state of the Universe from our observations of it. Rather, these two parts of a final theory are theoretical proposals, inferred from partial data to be sure, but incorporating theoretical assumptions of simplicity, beauty, coherence, mathematical precision, etc. To test these proposals, we search among the conditional probabilities they imply for predictions of observations yet to be made with probabilities very near unity. When such predictions occur, we consider them as successes of the theory; when they do not, we reject the theory and propose another one.

Do we need a theory of the quantum state? To analyze this question, let us consider various degrees of theoretical uncertainty about it.

18.5.1 Total ignorance

In the ‘box’ cosmology model of Section 18.2, theoretical uncertainty about the quantum state can be represented by a density matrix ρ that specifies probabilities for its eigenstates to be $|\Psi\rangle$. Total ignorance of the quantum state is represented by ρ being proportional to the unit matrix. To illustrate this and the subsequent discussion, assume for the moment that the dimension of the Hilbert space is very large but finite. Then total ignorance of the quantum state is represented by

$$\rho_{\text{tot ign}} = \frac{I}{\text{Tr}(I)}, \quad (18.7)$$

which assigns equal probability to any member of any complete set of orthogonal states.

The density matrix given by Eq. (18.7) predicts thermal equilibrium, infinite temperature, infinitely large field fluctuations and maximum entropy [9]. In short, its predictions are inconsistent with observations. This is a more precise way of saying that every useful prediction depends in some way on a theory of the quantum state. Ignorance is not bliss.

18.5.2 What we know

A more refined approach to avoiding theories of the quantum state is to assume that it is unknown except for reproducing our present observations of the Universe. The relevant density matrix is given by

$$\rho_{\text{obs}} = \frac{P_{\text{obs}}}{\text{Tr}(P_{\text{obs}})}, \quad (18.8)$$

where P_{obs} is the projection on our current observations – ‘what we know’. Observations in this context mean what we directly observe and record here on Earth and not the inferences we draw from this data about the larger Universe. That is because those inferences are based on assumptions about the very quantum state that Eq. (18.8) aims to ignore. For instance, we observed nebulae long before we understood what they were or where they are. The inference that nebulae are distant clusters of stars and gas relies on assumptions about how the Universe is structured on very large scales that are, in effect, weak assumptions on the quantum state.

Even if we made the overly generous assumption that we had somehow directly observed and recorded every detail of the volume 1 km above the surface of the Earth, say at 1 mm resolution, that is still a tiny fraction ($\sim 10^{-60}$) of the volume inside the present cosmological horizon. The projection

operator P_{obs} therefore defines a very large subspace of Hilbert space. We can expect that the entropy of the density matrix Eq. (18.8) will therefore be near maximal, close to that of Eq. (18.7), and that its predictions will be similarly inconsistent with further observations.

In the context of anthropic reasoning, these results show that conditioning probabilities on ‘us’ alone is not enough to make useful predictions. Rather, in addition a theory of H and $|\Psi\rangle$ is required, as described in Section 18.4.

18.6 A final theory

Let us hope that one day we will have a unified theory based on a *principle* that will specify *both* quantum dynamics (H) and a unique quantum state of the Universe ($|\Psi\rangle$). That would truly be a final theory and a proper context for anthropic reasoning.

Acknowledgements

Appreciation is expressed to the Mitchell Institute for hospitality and to the National Science Foundation for partial support under grant NSF-PHY02-44764.

References

- [1] J. Barrow and F. Tipler. *The Anthropic Cosmological Principle* (Oxford: Oxford University Press, 1986).
- [2] J. B. Hartle. The quantum mechanics of closed systems. In *Directions in General Relativity, Volume 1: A Symposium and Collection of Essays in Honor of Professor Charles W. Misner's 60th Birthday*, eds. B.-L. Hu, M. P. Ryan and C. V. Vishveshwara (Cambridge: Cambridge University Press, 1993) [gr-qc/9210006].
- [3] J. B. Hartle. Spacetime quantum mechanics and the quantum mechanics of spacetime. In *Gravitation and Quantizations, Proceedings of 1992 Les Houches Summer School*, eds. B. Julia and J. Zinn-Justin (Amsterdam: North Holland, 1995) [gr-qc/9508023].
- [4] R. B. Griffiths. *Consistent Quantum Theory* (Cambridge: Cambridge University Press, 2002).
- [5] R. Omnès. *The Interpretation of Quantum Mechanics* (Princeton, NJ: Princeton University Press, 1994).
- [6] M. Gell-Mann. *The Quark and the Jaguar* (San Francisco: W. Freeman, 1994).
- [7] S. W. Hawking. The quantum state of the universe. *Nucl. Phys. B* **239** (1984), 257.
- [8] J. B. Hartle. Scientific knowledge from the perspective of quantum cosmology. In *Boundaries and Barriers, On the Limits to Scientific*

- Knowledge*, eds. J. L. Casti and A. Karlqvist (Reading, MA: Addison-Wesley, 1996) [gr-qc/9601046].
- [9] J. B. Hartle. The state of the universe. In *The Future of Theoretical Physics and Cosmology: Stephen Hawking 60th Birthday Symposium*, eds. G. W. Gibbons, E. P. S. Shellard, and S. J. Ranken (Cambridge: Cambridge University Press, 2003) [gr-qc/0209046].
- [10] J. B. Hartle. Quasi-classical domains in a quantum universe. In *Proceedings of the Cornelius Lanczos International Centenary Conference*, North Carolina State University, December 1992, eds. J. D. Brown, M. T. Chu, D. C. Ellison and R. J. Plemmons (Philadelphia: SIAM, 1994) [gr-qc/9404017].
- [11] A. Strominger. Baby universes. In *Quantum Cosmology and Baby Universes, Proceedings of 1989 Jerusalem Winter School for Theoretical Physics*, eds. S. Coleman, J. B. Hartle, T. Piran and S. Weinberg (Singapore: World Scientific, 1991).
- [12] S. W. Hawking. The cosmological constant is probably zero. *Phys. Lett. B* **134**, 403 (1984).
- [13] S. W. Hawking and T. Hertog. Populating the landscape: A top down approach. *Phys. Rev. D* **73** (2006), 123527 [hep-th/0602091].
- [14] S. Weinberg. The cosmological constant problems. In *Sources and Detection of Dark Matter and Dark Energy in the Universe*, ed. D. Cline (New York: Springer-Verlag, 2001) [astro-ph/0005265].
- [15] A. Vilenkin. Cosmological constant problems and their solutions. In *Astronomy, Cosmology and Fundamental Physics, Proceedings of ESO-CERN-ESA Symposium*, Garching, 4–7 March, 2002, eds. P. A. Shaver, L. DiLella and A. Giménez (Berlin: Springer, 2003), p. 70 [hep-th/0106083].

19

Micro-anthropic principle for quantum theory

Brandon Carter

Observatoire de Paris, Meudon

19.1 Introduction

As a prescription for ascribing *a priori* probability weightings to the eventuality of finding oneself in the position of particular conceivable observers, the anthropic principle was originally developed for application to problems of cosmology [1] and biology [2]. The purpose of this chapter is to provide a self-contained introductory account of the motivation and reasoning underlying the recent development [3] of a more refined version of the anthropic principle that is needed for the provision of a coherent interpretation of quantum theory.

In order to describe ordinary laboratory applications, it is commonly convenient, and entirely adequate, to use a ‘Copenhagen’ type representation, in which a Hilbert state vector undergoes ‘collapse’ when an observation is made. However, from a broader perspective it is rather generally recognized that such a collapse cannot correspond to any actual physical process.

A leading school of thought on this subject was founded by Everett [4], who maintained the principle of the physical reality of the Hilbert state, and deduced that – in view of the agreement that no physical collapse process occurs – none of the ensuing branch channels can be ‘more real than the rest’. This was despite the paradox posed by the necessity that they be characterized by *different* (my italics) ‘weightings’, the nature of which was never satisfactorily explained. This intellectual flaw in the Everett doctrine was commonly overlooked, not so much by its adherents, who were seriously concerned about it [5], as by its opponents, who were upset by its revolutionary ‘multi-universe’ implications.

The main alternative line of development was based on the (widely accepted) principle – which will be adopted as the starting point for the present work – that neither the specialized pure Hilbert space vector, nor

the von Neumann probability operator that replaces it in more general circumstances, is of an objective physical nature. Rather, they are merely mathematical prediction tools of an entirely subjective nature, as also is the collapse to which they are subjected if and when the relevant information becomes available. However, this approach also came up against a paradox, which was exemplified by the parable of ‘Wigner’s friend’ [6] (who, in the more detailed discussion below, I shall suppose to have been Schrödinger, the owner of the legendary cat). The problem – which became particularly acute in the context of cosmology – was how independent observers (such as Wigner and Schrödinger) can be dealt with objectively, on the same footing, by a probabilistic theory of an intrinsically subjective nature.

The longstanding problem of reconciling objectivity with subjectivity is solved here by the anthropic abstraction, which distinguishes a material observer (such as Wigner) from an abstract perceptor who may or may not perceive himself to be Wigner. The probability of such a perceptor must be attributed to some appropriate micro-anthropic principle of the kind that will be presented below [3].

19.2 Eventualities and observables

Although their ultimate purpose is to account for (and even predict) *events*, i.e. things that actually happen, physical (and other) theories are mainly concerned with what I shall refer to as *eventualities*, meaning things that may or may not actually happen.

Eventualities are subject to partial ordering, as expressible by a statement of the form $e_1 \subset e_2$, which is to be understood as meaning that if an eventuality e_1 happens as an actual event, then so does e_2 . On the understanding that the concept of eventuality formally includes the special case of the *null* eventuality, $\emptyset$, which by definition never happens, it can be assumed that any pair of eventualities, e_1 and e_2 , will define a corresponding combined eventuality $e_1 \cap e_2$, whose occurrence as an actual event implies and is implied by the occurrence, both at once, of e_1 and e_2 , so that we always have $e_1 \cap e_2 \subset e_1$. In particular, the condition for e_1 to be incompatible with e_2 will be expressible as $e_1 \cap e_2 = \emptyset$.

The kinds of (classical and quantum) theory that I know about are all *additive* in the sense that, for each pair of eventualities e_1 and e_2 , there will be a well defined sum $e_1 \oplus e_2$ that is an admissible eventuality such that $e_1 \cap (e_1 \oplus e_2) = e_1$. In such a case, it is commonly useful to introduce a corresponding concept of *complementarity*, whereby a set $\{e\}$ of eventualities

$e_1, \dots, e_N$ will be describable as complementary if the sum $s = e_1 \oplus \dots \oplus e_N$ is an event that must necessarily happen.

An important related concept – on which discussions of quantum theory are commonly based (though it is less fundamental than that of an eventuality) – is that of an *observable*. This term is used to describe a set $\{e\}$ of non-null eventualities that is subject to a condition not just of complementarity, but also of what may be termed mutual *exclusivity*. An awkward feature of this concept (one of the reasons why I prefer to attribute the primary role to eventualities rather than to observables) is that it is difficult to formulate in a manner that transcends the technicalities of the particular kind of theory under consideration.

For a theory that is classical, in a sense whose meaning will be clarified in Section 19.3, a pair of eventualities e_1 and e_2 can be considered mutually exclusive if they satisfy the incompatibility condition $e_1 \cap e_2 = \emptyset$. However, for a quantum theory such incompatibility is merely necessary, not sufficient, for exclusivity in the strong sense (defined below) that is required for observability.

19.3 The classical paradigm

Some of the simplest and most commonly used theories are of the kind describable as *deterministic*, which means that they consist of rules whereby appropriate input data (such as initial conditions) can be used to single out a restricted subclass of events that actually happen within a much broader class of conceivable eventualities. However, a much more widely applicable category of theories are those that are *probabilistic*. Instead of providing rules that clearly distinguish events that happen from other eventualities that do not, such theories merely provide prescriptions for ascribing what is usually called a *probability* (but what some people prefer to call a *propensity*) – meaning a real number P in the range $0 \leq P \leq 1$ – to each of the relevant eventualities, in a manner that must naturally be consistent with the partial ordering. This means that $e_1 \supset e_2$ implies $P\{e_1\} \geq P\{e_2\}$ and, in particular, $P\{\emptyset\} = 0$. The category of probabilistic theories evidently includes deterministic theories as the special case for which the range of probabilities is restricted to two extreme values: $P = 1$ characterizing events and $P = 0$ characterizing other eventualities that do not actually happen.

A particularly important subcategory of probabilistic theories is that which includes the *classical* ones. For the description of a system A in a classical theory, the admissible eventualities will be identifiable as subsets of a corresponding set $I\{A\}$ that is endowed with an ordinary probability

measure, whose restriction to a subset $e \subset I$ gives the corresponding probability $P\{e\}$, while the complete set I can be interpreted as representing an eventuality that is certain, meaning that $P\{I\} = 1$. Such a theory will automatically be endowed with an additive structure, whereby any pair of eventualities e_1 and e_2 will not only have a combination given by the intersection $e_1 \cap e_2$, but will also have a well defined sum that is defined as the corresponding union $e_1 \oplus e_2 = e_1 \cup e_2$. Unlike in a quantum theory, its probability will then be given by $P\{e_1 \oplus e_2\} = P\{e_1\} + P\{e_2\} - P\{e_1 \cap e_2\}$.

The simplest example of a classical theory is the system consisting of a tossed coin, which can be described in terms of a total of four eventualities. Two of these eventualities are the independent possibilities e_1 for the tail to turn up and e_2 for the head to turn up. The other two (trivial) eventualities are their sum $I = e_1 \oplus e_2$, representing the certain event of something turning up, and the null eventuality $\emptyset = e_1 \cap e_2$, representing the impossible case of nothing turning up. The latter eventualities must always be characterized by $P\{I\} = 1$ and $P\{\emptyset\} = 0$. The non-trivial part of the probability distribution will be given in the unbiased version of the theory by $P\{e_1\} = P\{e_2\} = 1/2$ but could be different in biased versions. In such a (biased or unbiased) theory, the only non-trivial observable consists of the complementary pair of alternatives $\{e\} = \{e_1, e_2\}$, but of course there is also the trivial observable consisting just of I .

19.4 The Dirac–von Neumann paradigm

As in a classical theory, the admissible eventualities in a quantum theory for the description of a system A will be identifiable with subsets of a corresponding set $I\{A\}$. The essential new feature distinguishing a quantum theory is that I is endowed with a Hilbert space structure, and that the *admissible eventualities* are identifiable not with arbitrary subsets, but only with those that are *Hilbert subspaces*.

If e_1 and e_2 are the Hilbert subspaces representing a pair of admissible eventualities, their intersection $e_1 \cap e_2$ will also be a Hilbert subspace, representing the corresponding conjoint eventuality, but their union $e_1 \cup e_2$ will in general not have the structure of a Hilbert subspace and thus (unlike the classical case) will not represent an admissible eventuality. The eventualities of a quantum theory do, nevertheless, have an additive structure that is naturally induced by the Hilbert space structure: the sum $e_1 \oplus e_2$ is defined to be the Hilbert subspace that is *spanned* by the separate Hilbert subspaces e_1 and e_2 . What this means, using the standard notation scheme originally developed by Dirac [7], is that the state $|\Psi\rangle \in e_1 \oplus e_2$ if and only if $|\Psi\rangle$ is a Hilbert space vector having the form $|\Psi\rangle = |\Psi_1\rangle + |\Psi_2\rangle$ for some pair of

Hilbert space vectors such that $|\Psi_1\rangle \in e_1$ and $|\Psi_2\rangle \in e_2$. In the particular case for which every such pair of vectors satisfies the orthogonality condition $\langle\Psi_1|\Psi_2\rangle = 0$, the corresponding subspaces $e_1 \subset I$ and $e_2 \subset I$ will be describable as mutually orthogonal.

Orthogonality in this sense is what characterizes the kind of exclusivity required for the definition of what is generally known as an observable in the context of quantum theory. Thus an *observable* in a quantum theory for the system A (i.e. a qualitative observable, as distinct from a quantitative observable of the related kind to be discussed below) can be formally defined to consist of a complete set $\{e\}$ of mutually orthogonal Hilbert subspaces $e_1, \dots, e_N$, where the condition of completeness means that they span the entire Hilbert space $I\{A\}$, i.e. that $e_1 \oplus \dots \oplus e_N = I$.

For any particular eventuality, the corresponding subspace $e \subset I$ will determine and be determined by an associated Hilbert space projection operator $\mathbf{e} = \mathbf{e}^2$, defined so as to be automatically Hermitian by the conditions $\mathbf{e}|\Psi\rangle = |\Psi\rangle$ whenever $|\Psi\rangle$ lies in e and $\mathbf{e}|\Psi\rangle = 0$ whenever $|\Psi\rangle$ is orthogonal to the subspace e . The condition for a set $\{e\}$ of eventualities $\{e_i\}$ ($i = 1, \dots, n$) to constitute an observable is thus expressible as the condition that the corresponding operators should satisfy the orthogonality requirement $\mathbf{e}_i \mathbf{e}_j = 0$ for $i \neq j$ and the completeness condition $\sum_i \mathbf{e}_i = \mathbf{I}$, where $\mathbf{I}$ is the unit operator on I .

In the earliest versions of quantum theory, it was postulated that the relevant probabilities would be given just by the specification of a single state vector $|\Psi\rangle \in I\{A\}$, subject to the normalization condition $\langle\Psi|\Psi\rangle = 1$, according to a prescription expressible in the following familiar form:

$$P_{[\mathcal{O}]}\{e_i\} = \langle\Psi|\mathbf{e}_i|\Psi\rangle. \quad (19.1)$$

This is just a conditional probability, subject to the requirement that the relevant observation, $\mathcal{O}_e$, be actually carried out.

Soon after the original development of this Dirac–Heisenberg paradigm, it was recognized that a prescription of the simple form in Eq. (19.1) is too restrictive for typical cases in which the system A may interact with another (internal or external) system B . The extended system $\hat{A}$, consisting of the combination of A and B , will be characterized by a Hilbert space $\hat{I} = I\{\hat{A}\}$ which is constructed as the tensor product of $I\{A\}$ and $I\{B\}$. This means that a state vector $|\hat{\Psi}\rangle \in \hat{I}$ for the extended system will be expressible in terms of a basis of vectors $|\Phi_a\rangle \in I\{B\}$ satisfying the orthonormality condition $\langle\Phi_a|\Phi_b\rangle = \delta_{ab}$. It must therefore have the form

$$|\hat{\Psi}\rangle = \sum_a |\Phi_a\rangle |\Psi_a\rangle, \quad (19.2)$$

for some corresponding set of vectors $|\Psi_a\rangle \in I\{A\}$ that will not in general be orthonormal but must satisfy the condition $\sum_a \langle\Psi_a|\Psi_a\rangle = 1$ in order for the unit normalization condition $\langle\hat{\Psi}|\hat{\Psi}\rangle = 1$ to be satisfied. If e_i is a subspace of dimension $\mathcal{R}_i$ within the original Hilbert space $I\{A\}$ of dimension $\mathcal{N}\{A\}$, then it will determine a corresponding subspace $\hat{e}_i$ of dimension $\mathcal{R}_i\mathcal{N}\{B\}$ in the tensor product Hilbert space $\hat{I}$, where $\mathcal{N}\{B\}$ is the dimension of $I\{B\}$. Within the original Hilbert space $I = I\{A\}$, the corresponding projection operator will have rank given by its trace, $\mathcal{R}_i = \text{tr}\{\mathbf{e}_i\}$, while the corresponding operator $\hat{\mathbf{e}}_i$ of projection onto $\hat{e}_i$ in $\hat{I}$ will have rank $\mathcal{R}_i\mathcal{N}\{B\}$. According to the natural extension of Eq. (19.1), a unit state vector $|\hat{\Psi}\rangle$ in $\hat{I}$ will specify a (conditional) probability distribution given by

$$P_{[\mathcal{O}]}\{e_i\} = \langle\hat{\Psi}|\hat{\mathbf{e}}_i|\hat{\Psi}\rangle. \quad (19.3)$$

In order to express such a prescription within the simpler framework of the original Hilbert space $I\{A\}$ of the subsystem A with which we are particularly concerned, it is necessary to use a prescription of the kind whose development was attributed by Dirac to von Neumann. In the Dirac–von Neumann paradigm, instead of being specified by just a single state vector $|\Psi\rangle$, the (conditional) probability distribution (for the outcome of an observation $\mathcal{O}_e$ if actually performed) is specified by a Hermitian probability density operator $\mathbf{P}$ with unit trace on I according to the prescription

$$P_{[\mathcal{O}]}\{e_i\} = \text{tr}\{\mathbf{P} e_i\}. \quad (19.4)$$

This prescription is compatible with the original pure state paradigm, as specified by a single vector satisfying the unit normalization $\langle\Psi|\Psi\rangle = 1$, according to Eq. (19.1). The effect of this can be seen to be the same as taking $\mathbf{P} = |\Psi\rangle\langle\Psi|$ in the general formula Eq. (19.4). The advantage of the von Neumann type formulation in Eq. (19.4) is that it can also express the result of the more general prescription given in Eq. (19.3), whose effect can be seen to be the same as that of taking

$$\mathbf{P} = \sum_a |\Psi_a\rangle\langle\Psi_a|, \quad (19.5)$$

where the (generally non-orthonormal) set of vectors $|\Psi_a\rangle$ is specified by the decomposition in Eq. (19.2).

Many authors – particularly those influenced by the Everett doctrine [4] – have continued to hanker after the original Heisenberg-type paradigm,

meaning the supposition that the probabilities should ultimately be determined by a pure state in a very large all-embracing Hilbert space, characterizing the universe as a whole. Such authors – including Hawking [8] – have been inclined to regard the use of a von Neumann operator as a rather unsatisfactory approximation device that may be made necessary by our ignorance due to the regrettable loss of some of the relevant information in, for example, a black hole. However, my own attitude is like that of the distrustful insurance agent, who doubts whether what was alleged to have been lost was ever actually possessed. I personally see no reason why – to encompass more and more detailed microstructure and more and more extended macrostructure – the process of construction of successively larger and larger Hilbert spaces should ever come to an end. In other words, the search [9] for a single, ultimate, all-embracing ‘wave-function of the universe’, or even an ultimate, all-embracing von Neumann operator, may be like the pursuit of the proverbially elusive ‘Will o’ the wisp’. It seems more reasonable to accept that any system sufficiently simple to be amenable to our mathematical analysis can only be a model of an incomplete sub-component of something larger, and that it is therefore unreasonable to demand that it be describable by a pure state rather than a more general von Neumann operator. However that may be, advocates of the Everett doctrine would agree that there can in any case be no harm in working throughout in terms of the von Neumann paradigm, as will be done here, because it includes the more restricted Heisenberg-type pure state paradigm as a special case.

Before continuing, it should be remarked that the term *observable* has been used here to designate what – in a more pedantically explicit terminology – would be called a *qualitative observable*, in order to distinguish it from the *quantitative observables* that are definable as functions thereof. Thus, any qualitative observable $\{e\}$ determines and is determined by a corresponding equivalence class of quantitative variables, in which any particular member E is determined by a corresponding non-degenerate real-valued function E_i with the index labelling the admissible alternatives e_i for $\{e\}$. The condition for non-degeneracy of the function is to be understood as meaning that $E_i \neq E_j$ whenever $i \neq j$. In a quantum theory for a system characterized by a Hilbert space $I\{A\}$, such a quantitative observable will be identifiable with a corresponding Hermitian operator $\mathbf{E}$ whose eigenspaces are the Hilbert subspaces $e_i \subset I\{A\}$, while the corresponding eigenvalues are the real numbers E_i . One therefore has

$$\mathbf{E}|\Psi\rangle = E_i|\Psi\rangle \Leftrightarrow |\Psi\rangle \in e_i. \quad (19.6)$$

Such a quantitative variable E will have a mean (expectation) value $\langle E \rangle$ given by

$$\langle E \rangle = \text{tr}\{\mathbf{P}\mathbf{E}\}, \quad (19.7)$$

in which the operator $\mathbf{E}$ will be expressible in terms of the relevant projection operators $\mathbf{e}_i$ in the explicit form

$$\mathbf{E} = \sum_i E_i \mathbf{e}_i. \quad (19.8)$$

The simplest illustration is provided by the familiar Stern–Gerlach example, for which the observable $\mathbf{E}$ represents the spin energy of an electron (with respect to its own rest frame) in a uniform magnetic field. For this application, the relevant Hilbert space I has only two (complex) dimensions, being spanned by a subspace e_1 representing the eventuality that the spin be aligned with the magnetic field, and a subspace e_2 representing the eventuality that it be aligned in the opposite direction. Other eventualities, corresponding to alignment in other directions, will not be characterized by well defined energy values. The quantum analogue of the unbiased coin toss theory (considered in Section 19.3) is the unbiased spin theory, specified by adopting the isotropic probability distribution given (as the high temperature limit of an ordinary thermal distribution) by $\mathbf{P} = \mathbf{I}/2$.

19.5 Sensors and conditional probabilities

Having thus completed a brief overview of the basic quantum mechanical principles that are generally accepted as a matter of consensus, it is now necessary to approach the much more controversial issue of how these rather abstract principles should be interpreted in practice. In particular, how do we relate what might be observable in principle – in the abstract sense of the term as used above – to what is actually observed in the ordinary sense of the word, i.e. the recognition of the actual occurrence of an eventuality in some particular system under consideration?

The first, relatively uncontroversial, point that needs to be made is that the notion of an actual observation of an eventuality in a generic system is usually taken to involve an interaction with a specialized kind of system that I shall refer to as a *sensor*. This might consist of an artificial measuring apparatus of a simple and easily understandable kind, such as a Stern–Gerlach spin-orientation detector, or of something more mysterious, such as the brain of Schrödinger’s famous cat.

In order for an observable $\{f\}$ of a system B to be (exactly or approximately) observable, i.e. for the recognition of the actual occurrence of

a particular eventuality $f_j \in \{f\}$ to be feasible in practice, it is generally considered to be necessary not just that $\{f\}$ should be observable in the abstract sense formulated above, but also – more particularly – that it should be adequately correlated with a corresponding sensor observable $\{e\}$ in an appropriate sensor system A . The subsets $\hat{f}_j = f_j \otimes I\{A\}$ and $\hat{e}_i = e_i \otimes I\{B\}$ in the tensor product space $\hat{I} = I\{A\} \otimes I\{B\}$ of the combined system will naturally give rise to a conjoint observable $\{c\} = \{e\} \otimes \{f\}$, whose eventualities $\{c_{ij}\}$ are given by the intersection subspaces $\hat{c}_{ij} = \hat{e}_i \cap \hat{f}_j$. The probabilities of these conjoint eventualities will evidently form a matrix with elements given by

$$P_{ij} = P_{[O]}\{c_{ij}\}. \quad (19.9)$$

The first prerequisite for the desired correlation of $\{e\}$ and $\{f\}$ is that they have the same channel number, $\mathcal{N}_e = \mathcal{N}_f$, i.e. the same number of alternative eventualities, so that the matrix P_{ij} will be square. The final requirement for them to be adequately correlated is that (for a suitable index ordering) the matrix should be more or less diagonal, i.e. that for $i \neq j$ the probability P_{ij} should be zero or very small. (There is an extensive literature on the decoherence processes by which such diagonalization can be brought about [10].)

The conditions of the preceding paragraph are applicable both to classical and quantum systems. In the particular case of ordinary quantum systems, the observables $\{e\}$ and $\{f\}$ will give rise (in the extended Hilbert space $\hat{I}$) to corresponding sets of projection operators $\hat{\mathbf{e}}_i$ and $\hat{\mathbf{f}}_i$ that will automatically commute, $[\hat{\mathbf{e}}_i, \hat{\mathbf{f}}_j] = 0$, and whose products,

$$\hat{c}_{ij} = \hat{\mathbf{e}}_i \hat{\mathbf{f}}_j = \hat{\mathbf{f}}_j \hat{\mathbf{e}}_i, \quad (19.10)$$

will be the projection operators specified by the corresponding subspaces $\hat{e}_i \cap \hat{f}_j$. This means that (whether it is sufficiently diagonal or not) the probability matrix in Eq. (19.9) will be obtainable from the von Neumann operator $\hat{\mathbf{P}}$ on $\hat{I}$ in the form

$$P_{ij} = \text{tr}\{\hat{\mathbf{P}} \hat{\mathbf{e}}_i \hat{\mathbf{f}}_j\}. \quad (19.11)$$

It should be remarked that the relation described in the preceding paragraphs is *reflexive*, in the sense that if an observable $\{f\}$ of B is observable by A , then the corresponding observable $\{e\}$ of A will be similarly observable by B . A graphic illustration is provided by the gedanken experiment in which Schrödinger put his cat in a box that was equipped with an anaesthetizing mechanism triggered by a Stern–Gerlach detector. (Schrödinger originally envisaged a lethal mechanism, but that would have conflicted with

the Popperian desideratum of repeatability of the experiment.) One way of describing this is to take the detector to be the sensor A , whose reading will tell us about the state of the cat, considered as system B . However, by opening the box, one can see directly whether the cat is still awake, thereby using it as a sensor, A , that will tell us whether the spin measured by the detector, now considered as system B , was up or down. If one also reads the detector as well as opening the box, one can check the validity of the theory: an inconsistency might remind us of the likelihood for the cat to fall asleep spontaneously, with the implication that resort to a less satisfactory probability distribution, with non-vanishing off-diagonal elements, might be more realistic for subsequent repetition of the experiment.

It is commonly convenient to rewrite the expression for a joint probability of the kind given in Eq. (19.9) in terms of the corresponding conditional probability $P_{[i]} \{f_j\}$ for f_j given e_i in the form

$$P_{ij} = P_{[O]} \{e_i\} P_{[i]} \{f_j\}. \quad (19.12)$$

In the quantum context we are concerned with here, it can be seen that such a conditional probability for f_i will be given by the prescription whose form is analogous to that of Eq. (19.4), namely

$$P_{[i]} \{f_j\} = \text{tr} \{ \hat{\mathbf{P}}_{[i]} \hat{\mathbf{f}}_j \}. \quad (19.13)$$

Here, $\hat{\mathbf{P}}_{[i]}$ is the reduced probability operator associated with the subspace $\hat{e}_i$, given in terms of the original (unreduced) probability operator $\hat{\mathbf{P}}$ (on the extended space $\hat{I}$) by

$$\hat{\mathbf{P}}_{[i]} = P_i^{-1} \hat{e}_i \hat{\mathbf{P}} \hat{e}_i. \quad (19.14)$$

This formula automatically ensures that the reduced probability operator has the properties required for qualification as a von Neumann density in its own right, meaning that it is Hermitian with unit trace, i.e.

$$\text{tr} \{ \hat{\mathbf{P}}_{[i]} \} = 1. \quad (19.15)$$

The desideratum that $\{e\}$ should provide an approximate observation of $\{f\}$ is equivalent to the more restrictive requirement that the reduced probability operators should satisfy an approximation of the form $\text{tr} \{ \hat{\mathbf{P}}_{[i]} \hat{\mathbf{f}}_j \} \approx \delta_{ij}$.

19.6 The subjective nature of a probability operator

The consensus about what is meant (in the abstract sense) in quantum theory by a qualitative or quantitative observable and by a suitably adapted sensor does not extend to the question of what is meant by the occurrence

of an actual observation. There is, however, a rather general understanding that it is something that can be performed only by sensors of privileged class for which the title of *observer* is reserved. It would be rather generally agreed, in the context of the example referred to above, that this class would include Schrödinger himself but not his (gedanken) Stern–Gerlach detector. What is more litigious is the status of the cat; would its own discovery that it was still awake count as an actual observation?

Such awkward questions are particularly crucial in the context of what is commonly referred to as the naïve Copenhagen interpretation (‘naïve’ to distinguish it from other purportedly more sophisticated variants), according to which the von Neumann operator – or the state vector in the pure case – has the status of an objective physical entity that undergoes a (non-unitary) collapse

$$\mathbf{P} \mapsto \mathbf{P}_{[i]} \quad (19.16)$$

to the relevant reduced operator (or reduced state vector in the pure case). This reduced operator is constructed according to the procedure given by Eq. (19.14), when the outcome e_i is actually observed for an observable $\{e\}$.

The problem with this naïve Copenhagen doctrine is how to give a coherent prescription for deciding just when this collapse is supposed to occur. A relativity theorist would object at the outset that a question about when something occurs implicitly refers to the concept of time, a concept that is ultimately elusive and at best dependent on a subjectively arbitrary choice of reference system. However, there also is a more basic problem that arises, even when a reasonably unambiguous Newtonian-type temporal description is available as a good approximation. This would be the case for the cat experiment, even if not in other (e.g. cosmological) contexts.

This more basic problem [6] involves what is known as ‘Wigner’s friend’. Let us suppose that the friend in question was Schrödinger himself, and that Wigner was interested in the fate of the cat. Wigner would have had no direct access to the Stern–Gerlach detector, but would have been able to telephone Schrödinger to ask what had happened, thus using Schrödinger himself as the sensor, which prior to the opening of the box would have been in a mixed state. As far as Wigner was concerned, the relevant collapse process given by Eq. (19.16) would not have been applicable until the time of the telephone call, whereas from Schrödinger’s point of view it would have occurred at the earlier time when the box was opened, while the cat itself would have known even sooner if it had not been put to sleep. One might resolve the discrepancy between Schrödinger’s point of view and that of the cat by taking the line (which might be that of a theologian such

as Polkinghorne [11]) that the subhuman status of the cat disqualifies it from membership of the privileged class of genuine ‘observers’. However, no such specious evasion of the issue is available for the discrepancy between Wigner’s point of view and that of Schrödinger, whose equivalent status cannot be so easily denied.

The implication of this well known example is that the naïve Copenhagen interpretation cannot be coherently applied to cases in which several independent (human or other qualified) observers are involved. This means that it can ultimately be acceptable only to a (deliberate or subconscious) solipsist.

The obvious conclusion to be drawn from this is that a probability operator (or state vector in the pure case) should not be thought of as an objective physical entity, and that – as would be agreed even by followers of the Everett doctrine, who refuse such subjectivity – its collapse should not be thought of as a physical process, but as a mathematical step whose application will be appropriate whenever the necessary information, namely the observation of the particular eventuality e_i , becomes available. The operator collapse process described by Eq. (19.16) is thus merely the quantum analogue of the ordinary Bayesian reduction process $P \mapsto P_{[i]}$ for an ordinary classical probability distribution, whereby its *a priori* value is to be replaced by the corresponding *a posteriori* – i.e. conditional – value when the relevant information is supplied. Like the classical probability distributions P and $P_{[i]}$, the corresponding *a priori* and *a posteriori* von Neumann operators $\mathbf{P}$ and $\mathbf{P}_{[i]}$ should be considered to have a status that is not objective but intrinsically subjective.

A corollary of the foregoing conclusion is the anticipation that observers with different personal historical backgrounds should use *different* von Neumann operators, the *a priori* ones being very different and the *a posteriori* less so. However, there will tend to be *a posteriori* agreement when observational information is shared. In discussions of their different opinions about what is appropriate in cosmological contexts, authors such as Hawking and Vilenkin [9] tend to use the definite article for what they call ‘the’ state of the universe, but the reasoning I am developing here would suggest that such definiteness is unjustifiable, and that the most that is reasonable would be to propose ‘an’ *a priori* probability operator.

19.7 Everett’s concept of branch-channels

Having recognized the incoherence of the naïve Copenhagen interpretation, a newer school of thought, founded by Everett [4], has emphasized – correctly

according to the reasoning I am developing here – that there is no physical process of collapse of the probability operator. What is not so clearly correct, or even meaningful, is Everett’s concomitant conclusion that all the ensuing ‘branches of the universe’ remain equally real.

Before the validity of this doctrine can be discussed, it is necessary to explain what is meant by the branches – or more precisely branch-channels – in question. The origin of the idea dates back to before von Neumann, when it was assumed that the relevant probability distribution would be provided by a pure state, as specified by a unit Hilbert space vector that could be represented as a sum, $|\Psi\rangle = \sum_i |\Psi_i\rangle$, of eigenvectors $|\Psi_i\rangle \in e_i$ of the observable $\{e\}$ under consideration. The observation process was commonly described as having a first step consisting of splitting $|\Psi\rangle$ into the set of alternative projections,

$$|\Psi_i\rangle = \mathbf{e}_i |\Psi\rangle, \quad (19.17)$$

onto the relevant eigenspaces. These were described (rather misleadingly) as branches.

According to the naïve Copenhagen doctrine, the observation process would be completed by a second step, consisting of a collapse, whereby the set would be replaced by a single appropriately renormalized branch vector, $P_i^{-1/2} |\Psi_i\rangle$, that would turn up with the corresponding conditional probability $P_i = \langle \Psi_i | \Psi_i \rangle$. On the other hand, the Everett doctrine denied the occurrence of the collapse as a physical process, with the implication that the system would be subsequently describable as being in a mixed state, for which the corresponding von Neumann operator would have the form [12]

$$\mathbf{P} = \sum_i |\Psi_i\rangle \langle \Psi_i|. \quad (19.18)$$

This represents what I shall call the *provisional* probability operator, in order to distinguish it from the relevant (pure) *a priori* probability operator, given by

$$\mathbf{P}_{(0)} = |\Psi\rangle \langle \Psi|, \quad (19.19)$$

and whichever *a posteriori* probability operator,

$$\mathbf{P}_{[i]} = P_i^{-1} |\Psi_i\rangle \langle \Psi_i|, \quad (19.20)$$

may turn out to apply.

If the presumption that the system was initially in a pure state is replaced by the more general supposition that it was in an initial state describable

by an *a priori* probability operator, $\mathbf{P}_{(0)}$ say, consisting of an arbitrary sum of pure state operators, then – by considering the effect on each member of such a sum – it can be seen that the effect of the first step of the observation process described above will be to provide a provisional probability operator given no longer by the simple formula Eq. (19.18) but by the more general prescription

$$\mathbf{P} = \sum_i P_i \mathbf{P}_{[i]}. \quad (19.21)$$

This is known as Luder’s rule [13], in which the operators $\mathbf{P}_{[i]}$ are the *a posteriori* probabilities for the relevant output channels, i.e. the relevant eventualities e_i , which are what Everett referred to as ‘branches’. In accordance with Eq. (19.14), these *a posteriori* probability operators, and the corresponding probabilities, are given in terms of the *a priori* probability operator $\mathbf{P}_{(0)}$ by

$$\mathbf{P}_{[i]} = P_i^{-1} \mathbf{e}_i \mathbf{P}_{(0)} \mathbf{e}_i, \quad P_i = \text{tr}\{\mathbf{P}_{(0)} \mathbf{e}_i\}, \quad (19.22)$$

and it is to be noted that they are also recoverable, using expressions of the same form,

$$\mathbf{P}_{[i]} = P_i^{-1} \mathbf{e}_i \mathbf{P} \mathbf{e}_i, \quad P_i = \text{tr}\{\mathbf{P} \mathbf{e}_i\}, \quad (19.23)$$

from the ensuing provisional probability operator given in Eq. (19.21).

19.8 The deficiency of the Everett interpretation

Before exposing the essential deficiency of the Everett doctrine, I would like to rectify an additional misconception to which it has given rise. In its usual presentation, the use of the term ‘branch’ is motivated by the notion that the number of relevant channels increases whenever an observation is made. It is important to recognize that this idea – of perpetual multiplication of the relevant number of branch-channels – is, as a general rule, misguided. It is based on the – rarely realistic – presumption that the *a priori* state of the system under consideration is pure, consisting just of a single branch-channel, whereas in a generic case (for the reasons discussed above) $\mathbf{P}_{(0)}$ will already be mixed, involving as many branch-channels as $\mathbf{P}$, so no actual increase occurs. It is thus more appropriate as a metaphor to speak of channels rather than branches, which is why I have chosen, as a compromise, to use the term branch-channel.

In any case, even if the initial state really were pure, the commonly accepted idea that – as more and more information is obtained by successive

observations – the number of branches will go on increasing is also unrealistic for another reason, which is that a given finite system cannot continue to acquire information without limit. After a certain amount has been acquired, the system will saturate, so that further information will be able to be taken into account only by a (Landauer-type [14]) process involving the erasure of previously recorded information in order to release the necessary memory space. The number of channels available for useful observation can at most be a small fraction of the number of dimensions needed for a complete physical representation of the sensor, which in practice (if he, she or it is a system constituted from a finite number of molecules with a finite total energy in a finite volume) will, of course, be limited.

Bounded though it must be, the number of branch-channels – meaning the number of eventualities that may be observationally distinguished – in a given (human or other) sensor system can indeed be very large. It is this consideration that has exposed the Everett proposal [4] that all the branches are ‘actual, none any more real than the rest’ to the criticism [15] that it entails a ‘bloated ontology’. However, as I have previously remarked [16], as far as the scientific desideratum of Ockham’s razor (meaning economy of formulation) is concerned, it does not matter how extensive or otherwise the ensuing ‘ontology’ may be.

A more serious reason for dissatisfaction with the Everett doctrine of quantum theory is its failure to apply its own declared rules in a coherent manner, which has made the question of the interpretation of this ‘interpretation’ the subject of much discussion [5, 17]. The assertion that the branches are ‘actual’ seems to imply their ontological reality, but Everett’s categorical denial that any one is ‘more real than the rest’ is followed by the Orwellian admission [4] in a subsequent paragraph that ‘in order to obtain quantitative results’ the branches must be given ‘some sort of quantitative measure (weighting)’.

The aim of the Everett programme, as expressed by De Witt [17], is to construct a theory ‘in which it makes sense to talk about the state vector of the whole Universe. This vector never collapses, and hence the Universe as a whole is deterministic’. The troublesome problem [18–20] is how to use such an ultimately deterministic model to obtain the probabilistic predictions that work so well in local applications of quantum theory. As Graham [5] puts it ‘Everett attempts to escape from this dilemma by introducing a numerical weight for each world’. The work of Graham and of Hartle [21] has shown that Everett’s ‘weighting’ scheme does successfully reproduce the usual probabilistic predictions, so much so that the distinction between the terms ‘weighting’ and ‘probability’ can be seen to be merely semantic.

Changing its name to ‘weighting’ (or ‘propensity’, which is another traditionally favoured alternative) does not solve the problem of interpreting the meaning of the ‘probability’ that is involved.

It is clear that Everett and his followers have so far failed to achieve their declared objective. Their bold attempt to solve the – originally local – interpretation problem by reintroducing determinism at a global level has been helpful for providing a deeper understanding of many of the issues involved, but the question of how much ‘reality’ should be attributed to the probabilistically ‘weighted’ branch-channels has nevertheless remained unsolved until now.

My purpose here is to present a recent clarification [3], whereby this issue is not so much decided as transcended. This is in conformity with the precept that questions of ontology are of a theological nature that is beyond the scope of ordinary science (whose modest ambition is to account for appearances, and not for ultimate reality, whatever that may mean). The anthropic approach described below provides a framework in which an intellectually coherent interpretation can be provided in a manner that leaves plenty of scope for adjustment, and that is compatible not only with an (unbloated) ‘oriental’ option, in which hardly any of the relevant branches need be considered to be ‘real’, but also with a (scientifically indistinguishable but theologically very different) ‘occidental’ option, in which they might all be describable as ‘actual’.

19.9 The side issue of the provisional distribution

Whereas zealous adherents of the Everett doctrine – and *a fortiori* of the naïve version of the Copenhagen interpretation that was discussed above – would have it that some sort of objective reality can be attributed to the state vector on a sufficiently large scale, and hence to the probability operator that would be relevant on a more local scale, most other schools of thought, including less naïve versions of the dualistic Copenhagen interpretation, would concur with the supposition adopted here to the effect that such entities are essentially of a subjective nature. This contrasts with the status of the Hilbert space operator algebra of eventualities and observables, which have a more objectively well defined nature. According to this principle, the amplitudes (and corresponding ‘weightings’) of Everett-type branches should be considered as ultimately subjective, whereas the branches themselves can be considered to be objective. This does not, of course, entail that such mathematical structures are ‘real’ in any ontological sense.

Before leaving the subject of the ‘branching’ process (misnamed because the number of branches involved in the description of a subsystem need not increase, and might even decrease, when an interaction occurs), it is worth commenting further on the nature of the process whereby an *a priori* probability operator $\mathbf{P}_{(0)}$ is replaced by the corresponding provisional probability operator $\mathbf{P}$ given by Eqs. (19.21) and (19.22). The original discussions of this process were formulated in terms of what Dirac [7] referred to as the Schrödinger picture, wherein states are considered to have a time dependence in which the evolution from an initial time $t_{(0)}$ to a later time t is given by an operator transformation $\mathbf{P}_{(0)} \mapsto \mathbf{P}$ that will be given, in the special case of a pure state for an isolated system, by a corresponding vector transformation $|\Psi_{(0)}\rangle \mapsto |\Psi\rangle$. In the special case of an isolated system, such a transformation will be given by a unitary operator $\mathbf{U}$ (that is continuously generated by some Hermitian Hamiltonian) according to prescriptions of the standard form $|\Psi\rangle = \mathbf{U}|\Psi_{(0)}\rangle$ and $\mathbf{P} = \mathbf{U}\mathbf{P}_{(0)}\mathbf{U}^{-1}$. However, the transformation will in general be of a less simple (non-unitary) type when interaction with an external system is involved. The idea, as discussed by von Neumann, was that the preparation of an actual experimental observation should involve an arrangement whereby a transformation of this latter (non-unitary) type produced a provisional probability operator $\mathbf{P}$ of the required form. This is given by the Luder formula, Eq. (19.21).

As originally pointed out by Dirac [7], a representation in terms of such a Schrödinger picture can be translated into an equivalent representation in terms of the kind of Heisenberg picture that has been implicitly adopted throughout the present discussion. In this kind of representation, the relevant state vector $|\Psi\rangle$ or probability operator $\mathbf{P}$ is considered to be time-independent, and the effect of Schrödinger-type time translations is allowed for by corresponding transformations of the relevant observables and their constituent eventualities. In the special case of an isolated system, these transformations will be of the standard unitary type, so that, for example, if $\mathbf{e}_{(0)}$ is the projection operator corresponding to some particular eventuality at a time $t_{(0)}$, then the corresponding time-transposed eventuality at a later time t will be given by

$$\mathbf{e} = \mathbf{U}^{-1}\mathbf{e}_{(0)}\mathbf{U}. \quad (19.24)$$

The essential advantage of using a picture of this kind is that there is no impediment to its extension to (general relativistic and other) applications, for which no globally well defined Newtonian-type time parametrization may be available, so that the concept of a time translation relation of the

form $\mathbf{e}_{(0)} \mapsto \mathbf{e}$ might make sense only for very particular locally related eventualities.

As seen from this Heisenberg (as opposed to Schrödinger) point of view, the process of preparation of an experimental observation in the manner prescribed by von Neumann should be thought of not as the replacement of an *a priori* probability operator $\mathbf{P}_{(0)}$ by a different provisional probability operator $\mathbf{P}$, but as the replacement of an initially envisaged (perhaps maladapted) observable $\{\mathbf{e}_{(0)}\}$ by an appropriately adjusted observable $\{\mathbf{e}\}$, with respect to which the probability distribution already has the required Luderian form.

From this point of view, there is no need to bother about any distinction between *a priori* and provisional probability operators (which – in view of the possibility of using Eq. (19.23) instead of Eq. (19.22) – were, in any case, equivalent for the practical observational purpose under consideration). What matters for the purpose of making what von Neumann would consider to be a satisfactory observation is the choice of a suitably adjusted observable $\mathbf{e}$. However, the main point I wish to emphasize at this stage is that – although it may be of technical interest in particular applications – the importance of the issue of obtaining a satisfactory observation in the sense specified by Luder’s rule has been greatly exaggerated, in so far as its relevance to the ultimate interpretation of the observations process is concerned. To start with, there is the consideration that the Luderian desideratum is obtainable not only by the non-trivial process described above, whereby $\{\mathbf{e}\}$ is adjusted to a previously chosen probability operator, but also by the trivial process whereby the subjective *a priori* choice of $\mathbf{P}$ is adjusted *ad hoc* to fit a prescribed observable $\{\mathbf{e}\}$, an adjustment that in no way diminishes the credibility of its implications, as can be seen from the equivalence of the prescriptions given in Eqs. (19.22) and (19.23).

A more fundamental reason why the question of the Luderian transition is irrelevant is that, when an observation has been actually carried out (not merely planned), one will be left just with a single confirmed eventuality e_i . Such a single eventuality might be incorporated with others to constitute a complete observable set (spanning the entire Hilbert space) in many different ways, whose substitution in the Luder formula, Eq. (19.21), would provide many different results. Nevertheless, however that might be, and regardless of any distinction that may or may not have been made between an *a priori* probability distribution $\mathbf{P}_{(0)}$ and a provisional probability $\mathbf{P}$, one will be left with an unambiguously specified *a posteriori* probability distribution $\mathbf{P}_{[i]}$, which is all that matters for the purpose of subsequent predictions one may wish to make.

The upshot is that someone (such as Wigner) concerned about Schrödinger's cat should use the *a posteriori* distribution when the relevant information has become available, and until then should just continue to use the ordinary *a priori* distribution. One should avoid getting sidetracked (as so many of Everett's followers have been) by intermediate Luderian technicalities, whose analysis is of little relevance to the two outstanding issues that remain. In addition to the question of interpretation, which will be addressed from an anthropic point of view below, the other outstanding issue is the usual practical Bayesian dilemma of how to decide quantitatively what *a priori* distribution should be used in a particular context – something that can sometimes be resolved just by symmetry considerations (as in the coin-tossing example described above).

19.10 Perceptions and perceptibles

An important idea that was latent in much of the preceding discussion is that some privileged eventualities and observables are more naturally significant than others. In the discussion of Luder's rule, it was remarked that this can be interpreted as selecting a privileged class of observables, but I should emphasize before continuing that privilege of that kind is not what I am concerned with here, because it is ultimately dependent on an arbitrary subjective choice of the relevant *a priori* probability distribution. The kind of privilege I am concerned with is something that depends on the essential nature of the system under consideration, in a manner that is independent of the choice of the probability distribution. This is something that could be said about Bohm's idea [13] of privileging position with respect to its dynamical conjugate, namely momentum, but that particular choice is something that would not seem very natural to the numerous physicists whose mental life is based in Fourier space.

The kind of privilege that seems to me more relevant for the interpretation question is something that would be rather generally recognized as being imposed by the circumstances in particular cases. It is exemplified most simply by the existence of a privileged choice (determined by the background magnetic field) for the the particular spin eventualities characterized as 'up' and 'down' in the Stern–Gerlach experiment discussed above. It is also exemplified by many familiar kinds of apparatus, such as can be found in scientific laboratories, and increasingly in ordinary homes, whose output is typically presented in terms of what – at the highest resolution – usually turns out to consist of simple integer valued observables, such as the alternative eventualities in the range from 0 to 9 for a digit in a counter output, or

the binary alternatives for a particular pixel on a screen to be ‘on’ or ‘off’. It is mathematically possible to use other bases for a Hilbert space description of such systems, for example by working with eventualities defined as linear superpositions of ‘on’ and ‘off’ states of screen pixels, but that is evidently not the kind of treatment for which such an apparatus was intended by its designer.

Although the degree of complexity of the systems involved is very different, it seems to me that there is a rather strong analogy between the special role of the ‘on’ and ‘off’ states for a pixel on a screen and the ‘awake’ and ‘sleeping’ states of Schrödinger’s cat. The privileged status of the particular eventualities in question can be accounted for as the result of a process of design that is attributable in the first case, not just to an individual engineer, but to the collective activity of a scientific community, while it is attributable in the second case to a very long history of biological evolution by Darwinian selection. Having said this about the cat, the next thing to be said is that the same applies to Schrödinger and Wigner, for whom the relevant privileged eventualities are states of mind corresponding to the realization of whether or not the cat is awake.

Whatever doubts we may have about the status of the cat, we must recognize that Schrödinger and Wigner are closely analogous to ourselves (i.e. the author and presumed readers of this essay), which means that insight into the working of their minds can be obtained from our own experience. The only eventualities about whose reality we can be sure are the conscious perceptions in our own minds (of which some, namely those occurring in dreams, are evidently uncorrelated with anything outside). These correspond to the ‘mind states’ whose essential role has been recognized by authors such as Donald [22], Lockwood [23] and particularly Page [24], whose line of approach is followed here. It seems reasonable to postulate the validity of Page’s principle, according to which conscious perceptions are the only eventualities that can be considered actually to happen. It also seems reasonable to make the concomitant postulate that these perceptions must belong to some restricted class of privileged eventualities of the kind discussed in the preceding paragraph. I shall refer to the eventualities of this subclass as perceptibles.

In his ‘sensible quantum theory’ [24], Page has attributed a privileged role to a class of observables that he refers to as ‘awareness operators’, which I interpret to mean observables whose individual constituent eventualities are the perceptibles introduced in the previous paragraph. Page has used these particular operators to develop a refined version of the Everett interpretation, in which the branches – or as I would prefer to say,

channels – that matter are specified with respect to these awareness operators. Thus, whereas Everett’s original version might attribute ‘actuality’ to branches defined with respect to observables of a rather arbitrary kind, Page’s more refined version would attribute ‘actuality’ only to branches of an appropriately restricted kind, namely the channels that are specified by perceptibles. Having thus provided a much clearer idea of which channels are actually needed, Page was still left with the problem of interpreting what, following Everett’s evasive example, he referred to as their ‘weighting’. The point at which Everett stumbled was in trying to reconcile his recognition that the weighting was needed with his preceding claim that all the branches were equally real. Page came up against the same problem with respect to the claim to the effect that all the perceptibles are actually perceived.

19.11 The anthropic abstraction

A corresponding paradox is reached from a rather different angle in the approach I am developing here, which is in agreement with that of Page [24] in so far as the special role of perceptions is concerned, but differs in affirming that the weighting in question must be considered to have an essentially subjective and probabilistic nature. The intrinsically probabilistic nature of models of the kind advocated here raises the problem of what it can mean to attach a probability to the actuality of an eventuality in the mind of someone else if the only events one can actually observe are those occurring in one’s own mind.

Before presenting what I think is the only acceptable way of dealing with this paradoxical problem, I would mention two less satisfactory ways of resolving the issue that have been suggested in the past. The first way is that of the solipsist, who would deny the existence of any conscious perceptions other than his (or her) own [20], with the implication that the apparent analogy between oneself and others (such as Schrödinger) is merely a superficial illusion. The second way – which (unlike that of the solipsist) has been followed up by many physicists, starting with de Broglie – is to revert to a deterministic description of the world, providing a theoretically well defined answer to the question of what really happens by denying the (experimentally well established) validity of the essentially probabilistic description provided by orthodox quantum theory. Neither the first nor the second of these ways can be said to resolve the paradox; they merely evade the issue by dropping one or other of the essential (experimentally motivated) elements of the problem, which is that of providing an inherently probabilistic

treatment of perceived reality that respects the apparent symmetry between different people.

A historical analogy is provided by the incompatibility between Maxwellian electromagnetism and Newtonian gravity, which was ultimately resolved by their unification in Einstein's General Relativity. The problem to be dealt with here is that of reconciling subjective probability with objective reality. The only way that I know of solving this problem in a satisfactory manner is the anthropic approach, which faces the issue head on [3] without denying the validity of the considerations that lead to the paradox.

It is worth emphasizing, by the way, that the problem is not specifically a problem of quantum theory, but also arises in probabilistic versions of classical theory, as was recognized, I suspect, by many of those who were hostile to anything associated with the name of Bayes. The importance in this context of the quantum revolution is that it changed the status of Bayesian theorists from that of radicals (because they were willing to abandon determinism) to that of reactionaries (because they continued to use old fashioned Boolean logic).

The situation, as I understand it, is as follows. Suppose that to describe a system that includes ourselves (but, for the sake of finiteness, perhaps not the whole of the Universe) we have set up some (classical or quantum) theory that provides probabilities for an extensive class of eventualities. This class includes a specially privileged subclass of eventualities that I shall refer to as perceptibles, which are the only ones that can be actually observed as conscious perceptions. The set of such perceptions (not just yours and mine, but also those of everyone else) can be described as objective, and it is the only thing in the theory that can be considered to be real

We thus have an objective model attributing probabilities to perceptibles. But what sense can it make to attribute a probability to an observation you cannot make? If you are Wigner, what sense can it make – even in a classical theory – to use an objective distribution attributing probability to something that can only be known by Schrödinger? The contradiction arises when Schrödinger makes the Bayesian transition to the relevant *a posteriori* distribution, while Wigner continues, for the time being, to use the *a priori* distribution. How in these conditions can either of these distributions be considered to be objective?

The resolution to this paradox is provided by what may be called the anthropic abstraction (so called because it underlies that which I designated – perhaps inaptly – as the anthropic principle [25]). The paradox

that arises in this case (as in many others) can be attributed to an unnecessary assumption that has been consciously or subconsciously taken for granted. The unnecessary assumption is that of knowing in advance who one is. The *anthropic abstraction* consists in refraining from assuming in advance that one has the identity of some particular sensorial observer in the model, so that one's status *a priori* is that of what I shall refer to as an abstract *perceptor*. It is not until the actual happening of the perception that one can know whether one is Schrödinger, Wigner or whoever else may be included in the model.

It is, of course, to be understood that the perceptible eventualities that are involved in this anthropic approach cannot just be of the elementary type exemplified by the observation that someone else is awake, but that they need to include eventualities of the more complicated kind known as *consistent histories* [26]. The sort of eventuality that needs to be envisaged is not simply that of finding oneself to be Schrödinger, but that of finding oneself to be Schrödinger at a particular instant in his life, with all the memories he would have had at that moment.

The use (which I see no satisfactory way of avoiding without reverting to determinism) of the anthropic abstraction entails the need to adopt some kind of anthropic principle, by which I mean some kind of prescription for attributing appropriate probabilities to the relevant perceptible eventualities. The rather crude kind of anthropic principle that I have put forward on previous occasions [2] was concerned with the attribution of probability to entire observer systems (such as those associated with the names of Schrödinger or Wigner) without getting into the details of particular moments in their lives. For the applications I was then considering, it was sufficient to use a crude statistical treatment attributing equal weight to all terrestrial or extraterrestrial observers who can be considered to be sufficiently like ourselves to be describable as 'anthropic'. However – as several authors have already remarked [24, 25, 27] – the more detailed applications I have been considering here (particularly those involving quantum effects) require the use of a more refined kind of anthropic principle [3], which will distinguish not just between anthropic individuals, but also between different instants in the lives of such individuals.

The question that naturally arises at this point is whether it can suffice to use just the probability weightings that are directly provided by orthodox quantum theory (such as has been discussed above), in conjunction with some prescription for deciding which of the many mathematically defined eventualities in the model should be considered to have the privileged status of perceptibility.

19.12 Uniqueness of the perceptor?

In the subsequent subsections I shall address the scientifically important question of the attribution of the required anthropic probability. However, before doing so, I would like to digress by mentioning another question of a less scientific nature that might become a subject of philosophical discussion in the future.

This is the question of the nature of what I have referred to as a perceptor, whose actual perceptions are the only entities within the model that are considered to be real (which is not to deny the reality, in some theological sense, of other entities beyond the scope of the model). The perceptor acquires an *a posteriori* identity (of an ephemeral nature) as a material observer (such as Schrödinger) on the occasion of an actual perception, but what about the immaterial identity the perceptor might have *a priori*?

Is the perceptor unique? The notion that all anthropic observers might just be avatars of a single perceptor will not seem strange to anyone familiar with oriental (Hindu or Buddhist) religious tradition. (A scientific analogy that comes to mind is Feynman's idea that the universe is inhabited only by a single electron, which is able to follow all the worldlines that we usually attribute to distinct electrons by also following – but in a time-reversed sense – the worldlines that we attribute to positrons.) The obvious Wheelerian epithet for the succinct encapsulation of this idea – namely that we all share the same abstract identity – is *solipsism without solipsism*.

The postulate of a unique perceptor has the advantage of being particularly economical in the sense required by Ockham's razor. Nevertheless, in the framework of the occidental (Judaean-Christian-Islamic) religious tradition, it might seem more natural to suppose that there are many distinct perceivers. What is not permissible, however tempting it may seem, is to suppose that distinct perceivers are correlated with distinct anthropic observers, such as Schrödinger and Wigner; the essence of the anthropic abstraction is that a perceptor has the potential for actualization in any observer state that has a non-zero probability amplitude. The only way you, as a material observer, can claim an exclusive monopoly of the potential for actualization of your own perceptor is by adopting an *a priori* probability distribution that attributes no weight to anyone other than yourself, in other words by adopting the (unacceptable) autocentric attitude describable as *solipsism with solipsism*.

For someone whose objection to the Everett doctrine was based not on its failure to follow its own declared rules, but on the ontological bloating [15] implicit in the many-universes doctrine, the present idea that one might

adopt a many-perceptor doctrine might be felt to be even worse. Whereas the number of Everett branch-channels is restricted, as I have remarked above, by the limited information content for any finite system, there is no limitation at all on the number of distinct perceptrors that might be conceived to exist, and that might all have a chance of undergoing the experience of being Schrödinger at some moment in their lives.

The idea that there might be an unlimited number of distinct perceptrors may be abhorrent to anyone for whom ontological economy is a desideratum, but on the other hand it might be extremely attractive to those who still hanker after determinism. Indeed, for those who consider that – in order to be meaningful – the concept of probability must be defined in terms of frequencies of the outcome of many identical performances of the same experiment, the many-perceptor doctrine can provide what is desired. If the number of perceptrors is vastly larger than the number of anthropic observers in the model, then each observer state (even those that are relatively improbable) would actually be perceived by a large number (albeit a small fraction) of the perceptrors. This would provide the desired frequency interpretation for the probability distribution. By using the anthropic abstraction in this ontologically uninhibited manner, it is at last possible to deliver what the Everett programme sought, which may be epitomized as *probability without probability*.

Multiplication of the number of sensors is not the only way of obtaining probability without probability, if that is what is desired. Another number whose magnification can achieve the same result is the number of perceptions that each particular perceptor is allowed to make. The supposition that there are a large number of perceptrors, each allowed to make only a small number of perceptions or possibly only one, is ontologically equivalent to the supposition that there is just a single perceptor who is allowed to make a large number of perceptions. As far as ontology is concerned, all that counts is the total number of perceptions.

Whether – as in the oriental version of the anthropic interpretation – there is a unique perceptor, or whether – as in the occidental version – the number of perceptrors is large (even compared with the number of anthropic observers) – is an issue that belongs to the realm of theology rather than science. The same can be said about the (more ontologically relevant) number of total perceptions, which may seem important to those who believe in probability only when formulated in terms of frequencies, but which in no way affects the way the theory is actually applied in practice. All that matters for scientific purposes is the relative probability distribution for the perceptions, which will now be discussed.

19.13 Anthropic weighting: the proper ansatz?

On the basis of the discussion in the preceding sections, it seems reasonable to suppose that, from the point of view of a perceptor, the ‘net’ probability P of a particular perception e_i within a particular subsystem (representing the part of the universe under consideration) should be given by an expression of the form

$$P\{e_i\} = \mathcal{P}_e P_{[\mathcal{O}]}\{e_i\}. \quad (19.25)$$

Here, $P_{[\mathcal{O}]}\{e_i\}$ is the ordinary ‘gross’ classical or quantum mechanical probability (as calculated in the manner described above) for the particular perceptible eventuality e_i to occur on the occasion when the relevant Page-type awareness observable $\{e\}$ is actually observed, while $\mathcal{P}_e$ is the anthropic factor giving the probability for the perception to belong to that particular observable set. A sensor of the familiar macroscopic but localized kind – exemplified by an ordinary computer or a human observer – will be characterizable by a fairly well defined worldline with a proper time parametrization τ , in terms of which the anthropic probability factor will be expressible as

$$\mathcal{P}_e = \dot{\mathcal{P}} \Delta_e \tau, \quad (19.26)$$

where $\Delta_e \tau$ is the relevant proper time duration and $\dot{\mathcal{P}}$ is a corresponding probability rate, whose integral,

$$\mathcal{P} = \int \dot{\mathcal{P}} d\tau, \quad (19.27)$$

will be interpretable as the total probability for the perception to occur at some stage in the life of that particular observer.

Whereas the conditional probability – designated by P in Eq. (19.25) – is of the ordinary kind that is provided by the relevant classical or quantum physical theory for the system under consideration, the anthropic probability factor – designated by $\mathcal{P}$ (which is also conditional in so much as it is restricted to that particular system within the universe) – can only be provided by what I call an *anthropic principle*.

In my earlier discussions of applications that were not concerned with discrimination between individuals, but with averages over entire populations [2], it was good enough to suppose that – provided they were sufficiently similar to ourselves (motivating the rather debatable choice of the term anthropic) – the relevant total probability $\mathcal{P}$ per observer could be taken to be the *same* for each one. This is in accordance with what Vilenkin has referred to as a postulate of *mediocrity* and what I would refer to as a

postulate of *approximate symmetry*. The application of such a mediocrity postulate in the present context gave rise to what I call the *weak anthropic principle*, whose purport is that the anthropic probability factor should take a fixed value:

$$\mathcal{P} = \frac{1}{N}, \quad (19.28)$$

where N is the number of anthropic observers that come into existence within the system under consideration. So, if the system were scaled up to include a larger chunk of the Universe, with a larger population number N , then the value of $\mathcal{P}$ would be correspondingly scaled down.

The ordinary (weak) anthropic principle formulated in the preceding paragraph will evidently not be enough for more detailed purposes, such as comparison of the probability of finding oneself to be someone very short lived (as in the case of a child that dies in infancy) with that of finding oneself to be someone more long lived (as in the case of a normal adult). For such a purpose, the most naïve possibility is to adopt the ansatz which I would call the *proper* anthropic principle, meaning the postulate of a fixed universal value for the anthropic probability rate $\mathcal{P}$. This would be given numerically by

$$\dot{\mathcal{P}} = \frac{1}{\langle \tau \rangle N}, \quad (19.29)$$

where $\langle \tau \rangle$ is the average total proper lifetime of an anthropic observer in the system. In so far as the total probability over the total lifetime τ of an observer is concerned, adoption of the proper anthropic principle, represented by Eq. (19.29), evidently entails that Eq. (19.28) should be replaced by

$$\mathcal{P} = \frac{\tau}{\langle \tau \rangle N}. \quad (19.30)$$

The foregoing refinement of the original anthropic principle, represented by Eq. (19.28), should be good enough for a wide range of applications. However, for the purpose of comparing observers of very different kinds (for which the qualification anthropic might not be so appropriate), such as extraterrestrials and cats, not to mention babies in our own species, the plausibility of Eq. (19.29) is much less obvious.

19.14 Micro-anthropic principle: the entropic ansatz

A hint toward a more plausible (though not so easily applicable) alternative is discernible in the response to the eschatological problem posed by Islam [28] that was provided by Dyson, who suggested [29] that what really

matters is not the proper time duration of an interval, but how much information is effectively processed therein. There is, of course, room for discussion about how to quantify what is effectively processed (as opposed to what is merely stored in a memory), even in the case of an ordinary computer and hence much more so in the case of a feline or human mind. Estimating that the duration of a human ‘moment of consciousness’, which presumably corresponds to what is denoted here by $\Delta_e \tau$, has the same order of magnitude as supposed in the more recent work of Page [24], namely a significant fraction of a second, Dyson deduced (from the fact that the heat production of an entire human body is typically about 200 W at a temperature of 300 K) that the corresponding entropy production Q_e is of the order of 10^{23} bits. However, experience with the analogous problem for computers indicates that the amount of information S_e that can be judged to have been effectively processed by the mind itself during the corresponding period of perception – and the associated Landauer entropy production [14] – must have a vastly smaller value $S_e \ll Q_e$ that is not so easy to evaluate.

A plausible prescription for the evaluation of the processed information S_e will, however, be available if we have a sufficiently detailed (quantum not just classical) theory to characterize the Hilbert space projection operator $\mathbf{e}_i$ corresponding to a particular perception e_i under consideration. If we suppose that this particular perception belongs to a complete set of eventualities having the same rank (i.e. subspace dimension) $\mathcal{R}_e = \text{tr}\{\mathbf{e}_i\}$ constituting an observable $\{e\}$ in a Hilbert space of dimension $\mathcal{N} = \text{tr}\{\mathbf{I}\}$, so that the corresponding number of Everett-type branch channels is given by $\mathcal{N}_e = \mathcal{N}/\mathcal{R}_e$, then the associated information capacity will be given by

$$S_e = \log\{\mathcal{N}_e\} = \log\{\text{tr}\{\mathbf{I}\}\} - \log\{\text{tr}\{\mathbf{e}_i\}\}, \quad (19.31)$$

using a logarithm with base 2 if one wants to use Shannon’s bit units, or using a natural logarithm if one wants to use the entropy units preferred by physicists. This information capacity represents the maximum amount of information that can be given – for a probability distribution P_i ($i = 1, \dots, \mathcal{N}_e$) – by Shannon’s formula $S = -\sum_i P_i \log\{P_i\}$.

What I would propose is that Eq. (19.31) be used as an estimate of the amount of information that can be considered to be processed during the perception e_i , and that the corresponding anthropic probability should be postulated to be proportional to this, i.e. the required factor in Eq. (19.25) should be taken to be given by

$$\mathcal{P}_e = \alpha S_e, \quad (19.32)$$

where α is a fixed proportionality factor that is chosen so as to ensure the usual requirement that the total probability (over all the relevant world-lines) should add up to unity. According to this *micro-anthropic* principle – which might appropriately be described by the term *entropic* principle – the probability rate will not have a fixed value (as was postulated by the proper anthropic principle formulated above) but will be given by

$$\dot{\mathcal{P}} = \alpha \frac{S_e}{\Delta_e \tau}. \quad (19.33)$$

The advantage of using the term ‘entropic principle’ for this ansatz is that it emphasizes its virtue of being applicable in principle not just to observers qualifiable as anthropic, in the sense of being sufficiently similar to ordinary adult humans, but also to very different kinds, ranging from such familiar examples as babies and cats to the highly exotic extraterrestrial observers whose survival at extremely low temperatures was envisaged by Dyson [29]. A rather obvious application of this entropic principle is its use as evidence against Dyson’s conjecture that civilizations constituted by observers capable of surviving at the extremely low temperatures predicted for a non-compact universe in the distant future would be able to survive indefinitely with respect to not just proper time, but also any relevant information-processing measure. If this conjecture were correct, it would mean that the probability measure defined according to Eq. (19.33) by the entropic principle would diverge toward the future. The contrary prediction by Islam [28] that ‘it is unlikely that civilization in any form can survive indefinitely’ is therefore overwhelmingly favoured by the fact that we do not observe ourselves to be incarnated in asymptotically viable low temperature life-forms (if such can exist) but in carbon-based life-forms adapted to (cosmologically ephemeral) conditions of moderate temperature.

It must be emphasized that the preceding argument against the likelihood of long-term survival is entirely dependent on the acceptance of the kind of *a priori* probability distribution proposed (as a matter of choice, not merely as a tautology) by the anthropic principle and its entropic extension. Dyson’s writings in this and other analogous contexts – notably that of the prospects for our own terrestrial civilization [27] – give the impression that he personally prefers an *a priori* probability distribution of the traditional kind, based on what I would refer to as an autocentric (or pre-ordination) principle, to the effect that the attribution of non-zero weighting should be restricted retroactively to wherever one already finds oneself to be. Although it may be logically admissible as an alternative to principles of the anthropic

Table 19.1.

	e_1 : C awake	e_2 : C asleep	M: <i>gross</i> $\rightarrow$ net
e_3 : M awake, sees C awake	$P_{31} = 1/4$	$P_{32} = 0$	$1/4 \rightarrow 1/6$
e_4 : M awake, sees C asleep	$P_{41} = 0$	$P_{42} = 1/4$	$1/4 \rightarrow 1/6$
e_5 : M dreams C awake	$P_{51} = 1/8$	$P_{53} = 1/8$	$1/4 \rightarrow 1/6$
e_6 : M dreams C asleep	$P_{61} = 1/8$	$P_{62} = 1/8$	$1/4 \rightarrow 1/6$
C: <i>gross</i> $\rightarrow$ net	$1/2 \rightarrow 1/6$	$1/2 \rightarrow 1/6$	

kind, I would maintain that such an autocentric attitude is scientifically unreasonable, in so much as it violates the desideratum that comparable observers be treated objectively on the same footing. By adopting such an attitude [30], Dyson implicitly assumes for himself a privileged position to which other observers (such as Wigner and Schrödinger) are not admitted.

Before leaving the subject of logically admissible (even if not scientifically reasonable) alternatives to principles of the anthropic kind, I would mention a conceptually possible alternative that is quite the opposite of the autocentric deviation described in the previous paragraph. Instead of prescribing an *a priori* probability distribution with weighting restricted to material observers as in the anthropic case (or to a single privileged observer in the autocentric case), one might go so far as to envisage the attribution of non-zero weighting even to situations where no material observer is present at all. Such an unreasonably overextended weighting (as exemplified by the kind of ubiquity principle that was implicit in Dirac's original argument in favour of his now discredited theory [2,31] of varying gravitational coupling) might be logical if one could imagine oneself as some sort of disembodied spirit, but (as Dirac's example shows) it cannot be trusted for scientific purposes.

As a toy example to illustrate the application of this micro-anthropic principle, consider a gedanken experiment in which Schrödinger's cat, C, has an equal chance of being awake or dreaming, as also does its master, M, who – if awake – can see whether the cat is too, but – if asleep – has equal chance of dreaming that the cat is awake or asleep, whether or not it actually is. The cat is unconcerned about its master, and so has only two relevant mind states, e_1 or e_2 (awake or dreaming) with entropy $\mathcal{S} = \log 2 = 1$. Schrödinger has four relevant mind states, e_3 , e_4 , e_5 or e_6 with $\mathcal{S} = \log 4 = 2$, so his net probability is $2/3$, while the cat's is $1/3$. The conditional '*gross*' probability P and absolute 'net' probability P for the relevant eventualities are given in Table 19.1.

19.15 Local application

Whereas the term *entropic* principle has the advantage of avoiding any risk of misunderstanding that the range of applicability of the ansatz in Eq. (19.32) extends beyond observers of narrowly anthropic type, the alternative term *micro-anthropic* principle has the advantage of advertising the applicability of the principle (as of its *proper* predecessor defined by Eq. (19.29)) not just to the entire life of an observer, but to particular parts thereof. The question of whether one is more likely to find oneself nearer the beginning or end of one's life was raised in an epilogue by Leslie [27]. He suggested, on the basis of Everett's own (confusing) presentation of his doctrine [4], that the continual multiplication of the number $\mathcal{N}_e$ of relevant branches entailed a probability distribution that would be heavily biased towards the last moments of life. This assumes that the dogma that all the branch-channels are equally 'real' implies that the corresponding anthropic probability factor should be given by $\mathcal{P}_e \propto \mathcal{N}_e$, rather than by an expression of the entropic form $\mathcal{P}_e \propto \log\{\mathcal{N}_e\}$ that has been advocated here. Having safely survived, and thereby invalidated this alarming prediction, Leslie arrived at the observational conclusion – as argued on purely theoretical grounds at the beginning of this chapter – that this particular interpretation of the Everett doctrine is untenable.

According to the present analysis, the correct answer to Leslie's question is as follows. To start with, it is necessary to reject not only Everett's claim that the relevant branches are 'real' (which might be interpreted as meaning $\mathcal{P}_e \propto \mathcal{N}_e$), but also his attribution to them of an ordinary non-anthropic quantum probability weighting (which might be interpreted as implying the choice of a constant value for $\mathcal{P}_e$). This contradiction between Everett's preaching and practice is resolved in the present approach by what is interpretable as a compromise, according to which the appropriate formula has the logarithmic form $\mathcal{P}_e \propto \log\{\mathcal{N}_e\}$.

The replacement of a linear by a logarithmic dependence merely moderates, but does not avoid, the unrealistic implication that the probability distribution would strongly disfavour the earlier stages of a lifetime if Everett's branching metaphor were to be taken literally. It is therefore obvious that this aspect of what is commonly understood to be Everett's interpretation is also misleading and, as remarked above, it is very easy to see why. The idea of a rapidly increasing number of relevant branch-channels is something that may make sense in the case when, for example, one has just taken delivery of a new computer with entirely empty memory banks, but it will soon cease to be valid when saturation sets in, so that erasion becomes necessary to

release occupied space by converting the relevant information into Landauer entropy [14]. Concerning the human case, parents and primary school teachers know that even small children do a lot of forgetting as well as learning, while – as adulthood progresses – the ratio of what is learnt to what is forgotten goes on decreasing, so that it may ultimately become quite small as senility sets in. This means that the relevant number $\mathcal{N}_e$ of Everett branch-channels should normally reach a maximum – not a peak but a plateau – in midlife. It is to be understood that this statement refers to a smoothed average over diurnal variations, because the number of channels involved in conscious perception presumably undergoes considerable reduction during sleep, particularly during deep dreamless phases.

For practical probabilistic purposes, it is only relative values that matter. The intrinsically interesting question of the absolute height of the plateau is beyond the scope of the present investigation, but it is evident from physical considerations that $\mathcal{N}_e$ cannot be nearly as large as the (admittedly gigantic) value of $\exp\{Q_e\}$, where Q_e is the Dyson entropy number discussed above. This exceeds the corresponding Landauer entropy $S_e = \log\{\mathcal{N}_e\}$ (representing the amount of useful information processed during the perception [14]) by an enormous thermodynamical waste factor $W_e = Q_e/S_e \gg 1$. (In the days before valves were replaced by transistors, the relevant waste factors for computers were far worse even than those of their biological analogues, but the spectacular progress of engineering techniques in recent years has brought about an amazing rate of improvement.)

It is a noteworthy coincidence that Dyson's evaluation of Q_e in the human case [29] gave a value of the same order as the Avogadro number, which is interpretable as the number of molecules in a fraction of the order of 10^{-3} of the mass of a human body. If it is supposed that this fraction is comparable with the fraction of molecules that are metabolically active, then it can be deduced that the corresponding metabolic turnover time must be comparable to the mental time interval $\Delta_e\tau$, of the order of a fraction of a second, that was used in Dyson's evaluation.

This observation – that the estimated duration $\Delta_e\tau$ of a conscious perception is roughly comparable with a timescale characterizing metabolic processes throughout the body – may offer a significant clue as to the nature of the (still largely mysterious) mental processes involved. One thing that is clear is that the relevant value of $\Delta_e\tau$ can undergo considerable variation – lengthening, for example, in states of hibernation. In so far as the solution to the problem posed by Leslie is concerned, what is relevant is the age dependence of $\Delta_e\tau$. My impression, with which I think most people would agree, is that the typical duration of a moment of consciousness is relatively



Fig. 19.1. Some of the participants at the Clifford Centennial meeting organized by John Wheeler at Princeton in February 1970, assembling many of the people whose thoughts contributed to the synthesis presented here. In the front on the left are Bob Dicke with Eugene Wigner, in the centre are Stephen Hawking with the author, and behind them are Bryce DeWitt with Freeman Dyson.

short in early childhood and that, on average – modulo diurnal fluctuations through states of shallow or deep sleep – it increases monotonically throughout life. According to Eq. (19.33), this means that the maximum of the anthropic probability distribution need not coincide with the summit of the midlife plateau where the relevant branch-channel number $\mathcal{N}_e$ and its logarithm S_e are highest, but may actually occur at a more youthful stage.

19.16 Conclusions

The question of unicity or multiplicity (as posed by the title of this volume) arises at several levels in the approach developed here. One level (as discussed in Section 19.12) concerns the number of distinct perceptions involved; by postulating that this number is unlimited, the relevant probability weightings can be specified in terms of relative frequencies. One thereby obtains an interpretation of quantum mechanics that is compatible with Einstein's *desideratum* that 'God does not play dice', in the sense that uncertainty is no longer involved at an objective global level, but arises only at the subjective level of particular perceptions. It could therefore be said that *we* play dice, but God does not!

A deeper level concerns the plurality of the ‘we’ in the preceding statement; the basic question (also discussed in Section 19.12) is that of the number of distinct perceptors which can most economically be postulated to be just one (in the sense of Ockham). This issue is of no consequence in so far as purely scientific purposes are concerned, but it does have obvious ethical implications. The injunction to ‘love one’s neighbour as oneself’ acquires a new significance when one recognizes that the ‘neighbour’ may be another incarnation of ‘oneself’.

From a purely scientific point of view, the most interesting level (as discussed in Section 19.10) concerns the relevant numbers of Everett-type branches, which are determined by the solution to the problem of which eventualities should actually be characterized as perceptible. Whereas upper limits are obtainable in the manner suggested by Dyson (as discussed in Section 19.13), it is not so easy to see how to obtain lower limits on what should be considered perceptible.

References

- [1] B. Carter. Large number coincidences and the anthropic principle in cosmology. In *Confrontations of Cosmological Theories with Observational Data*, ed. M. Longair (Dordrecht: Reidel, 1974), pp. 291–298.
- [2] B. Carter. The anthropic principle and its implications for biological evolution. *Phil. Trans. Roy. Soc. A* **310** (1983), 347.
- [3] B. Carter. Anthropic interpretation of quantum theory. *Int. J. Theor. Phys.* **43** (2004), 721 [hep-th/0403008].
- [4] H. Everett. Relative state formulations of quantum theory. *Rev. Mod. Phys.* **29** (1957), 454.
- [5] N. Graham. The measurement of relative frequency. In *The Many Worlds Interpretation of Quantum Mechanics*, eds. B. S. De Witt and N. Graham (Princeton, NJ: Princeton University Press, 1973), pp. 229–253.
- [6] E. P. Wigner. On hidden variables and quantum mechanical probabilities. *Am. J. Phys.* **38** (1970), 1005.
- [7] P. A. M. Dirac. *Quantum Mechanics* (Oxford: Oxford University Press, 1958).
- [8] S. W. Hawking. The unpredictability of quantum gravity. *Commun. Math. Phys.* **87** (1982), 395.
- [9] A. Vilenkin. Quantum cosmology and eternal inflation. In *The Future of Theoretical Physics*, eds. G. W. Gibbons, E. P. Shellard and S. J. Ranken (Cambridge: Cambridge University Press, 2003), pp. 649–663 [gr-qc/0204061].
- [10] W. H. Zurek. Pointer basis of quantum apparatus: into what mixture does the wave function collapse? *Phys. Rev. D* **24** (1981), 1516.
- [11] J. C. Polkinghorne. *One World: The Interaction of Science and Theology* (Princeton, NJ: Princeton University Press, 1992).
- [12] J. von Neumann. *Mathematical Foundations of Quantum Mechanics* (Princeton, NJ: Princeton University Press, 1955).

- [13] J. Bub. *Interpreting The Quantum World* (Cambridge: Cambridge University Press, 1997).
- [14] V. Vedral. Landauer's erasure, error correction, and entanglement. *Proc. Roy. Soc. Lond. A* **456** (2000), 969.
- [15] J. Leslie. Cosmology, probability, and the need to explain life. In *Scientific Understanding*, eds. N. Rescher (Lanham and London: University Press of America, 1983).
- [16] B. Carter. The anthropic principle and the ultra-Darwinian synthesis. In *The Anthropic Principle*, eds. F. Bertola and U. Curi (Cambridge: Cambridge University Press, 1993), pp. 33–63.
- [17] B. S. DeWitt. The many universes interpretation of quantum mechanics. In *The Many Worlds Interpretation of Quantum Mechanics*, eds. B. S. De Witt and N. Graham (Princeton, NJ: Princeton University Press, 1973).
- [18] D. Deutsch. Quantum theory of probability and decisions. *Proc. Roy. Soc. Lond. A* **455** (1999), 3129 [quant-ph/9906015].
- [19] D. Wallace. Quantum probability and decision theory revisited. *Stud. Hist. Phil. Mod. Phys.* **34** (2003), 87 [quant-ph/0107144].
- [20] H. Greaves. Understanding Deutsch's probability in a deterministic universe. *Stud. Hist. Phil. Mod. Phys.* **35** (2004), 423 [quant-ph/0312136].
- [21] J. Hartle. Quantum mechanics of individual systems. *Am. J. Phys.* **36** (1968), 704.
- [22] M. J. Donald. A mathematical characterisation of the physical structure of observers. *Found. Phys.* **22** (1995), 1111.
- [23] M. Lockwood. Many minds' interpretations of quantum mechanics. *Brit. J. Phil. Sci.* **47** (1996), 159.
- [24] D. Page. Sensible quantum mechanics: are probabilities only in the mind? *Int. J. Mod. Phys. D* **5** (1996), 583 [gr-qc/9507024].
- [25] N. Bostrom. *Anthropic Bias: Observation Selection Effects in Science and Philosophy* (New York: Routledge, 2002).
- [26] M. Gell-Man and J. B. Hartle. Quantum mechanics in the light of quantum cosmology. In *Complexity, Entropy, and the Physics of Information*, ed. W. H. Zurek (Redwood City: Addison Wesley, 1991), pp. 425–458.
- [27] J. Leslie. *The End of the World* (New York: Routledge, 1996).
- [28] J. Islam. Possible ultimate fate of the universe. *Quart. J. Roy. Astron. Soc.* **18** (1977), 3.
- [29] F. J. Dyson. Time without end: physics and biology in an open system. *Rev. Mod. Phys.* **51** (1979), 447.
- [30] F. J. Dyson. Reality bites. *Nature* **380** (1996), 296.
- [31] R. H. Dicke. Dirac's cosmology and Mach's principle. *Nature* **192** (1960), 440.

Part IV

More general philosophical issues

Scientific alternatives to the anthropic principle

Lee Smolin

Perimeter Institute for Theoretical Physics, Waterloo

20.1 Introduction

I have chosen a deliberately provocative title, in order to communicate a sense of frustration I have felt for many years about how otherwise sensible people, some of whom are among the scientists I most respect and admire, espouse an approach to cosmological problems – the Anthropic Principle (AP) – that is easily seen to be unscientific. By calling it unscientific I mean something very specific, which is that it lacks a property necessary for any scientific hypothesis – that it be *falsifiable*. According to Popper [1–4], a theory is falsifiable if one can derive from it unambiguous predictions for practical experiments, such that – were contrary results seen – at least one premise of the theory would have been proven not to true. This introduction will outline my argument in a few paragraphs. I will then develop the points in detail in subsequent sections.

While the notion of falsifiability has been challenged and qualified by philosophers since Popper, such as Kuhn, Feyerabend and others,¹ few philosophers of science or working scientists would be able to take seriously a fundamental theory of physics that had no possibility of being disproved by an experiment. This point is so basic to how science works that it is perhaps worthwhile taking a moment to review its rationale.

Few scientists will disagree that an approach can be considered ‘scientific’ only to the extent that it requires experts who are initially in disagreement about the status of a theory to resolve their disagreements – to the fullest extent possible – by rational argument from common evidence. As Popper emphasizes, science is the only approach to knowledge whose historical record shows repeatedly that consensus was reached among well trained

¹ I will not discuss here the history and present status of the notion of falsifiability. My own views on the methodology of science are discussed elsewhere [5].

people in this way. But Popper's key point is that this has only been possible because proposed theories have been required to be falsifiable. The reason is that the situation is asymmetric; confirmation of a prediction of a theory does not show that the theory is true, but falsification of a prediction can show it is false.

If a theory is not falsifiable, experts may find themselves in permanent disagreement about it, with no possible resolution of their differences by rational consideration of the evidence. The point is that, to be part of science, X -theorists have to do more than convince other X -theorists that X is true. They have to convince all other hitherto sceptical scientists. If they do not aspire to do this, then – by Popper's definition – they are not doing science. Hence to prevent the progress of science from grounding to a halt, i.e. to preserve what makes science generally successful, scientists have an ethical imperative to consider only falsifiable theories as possible explanations of natural phenomena.

There are several versions of the AP [6–9].² There is, of course, the explicitly theological version, which is, by definition, outside of science. I have no reason to quarrel with that here. I also have no argument against straightforward consideration of selection effects, so long as the conditions invoked are known independently and are not part of a speculative theory that is otherwise unsupported by evidence. I will discuss this in some detail below, but – put briefly – there is a vast logical difference between taking into account a known fact (e.g. that most of the galaxy is empty space) and arguing from a speculative and unproven premise (e.g. that there is a large ensemble of unseen universes).

In recent discussions, the version of the AP that is usually proposed as a scientific idea is based on the following two premises.

- (A) There exists (in the same sense that chairs, tables and our universe exist) a very large ensemble of 'universes', $\mathcal{M}$, which are completely or almost completely causally disjoint regions of spacetime, within which the parameters of the Standard Models of physics and cosmology differ. To the extent that they are causally disjoint, we have no ability to make observations in universes other than our own.
- (B) The distribution of parameters in $\mathcal{M}$ is random (with some measure) and the parameters that govern our universe are rare.

This is the form of the AP most invoked in discussions related to inflationary cosmology and string theory, and it is the one I will critique in this chapter.

² My understanding of the logical status of the different versions of the Anthropic Principle was much improved by refs. [10]–[12].

Here is the basic argument for why a theory based on **A** and **B** is not falsifiable. If such a theory applies to nature, it follows that our universe is a member of the ensemble $\mathcal{M}$. Thus, we can assume that *whatever properties our universe is known to have, or is discovered to have in the future, at least one member of $\mathcal{M}$ has those properties. Therefore, no experiment, present or future, could contradict **A** and **B***. Moreover, since by **B** we already assume that there are properties of our universe that are improbable in $\mathcal{M}$, it is impossible to make even a statistical prediction that, were it not borne out, would contradict **A** and **B**.

There are a number of claims in the literature of predictions made from **A** and **B**. By the logic just outlined, these must all be spurious. We will examine the major claims of this kind and demonstrate that they are fallacious. This does not mean that the conclusions are wrong. As we shall see, there are cases in which the part of the argument that is logically related to the conclusion has nothing to do with **A** and **B** but instead relies only on observed facts about our universe. In these cases, the only parts of the argument that are wrong are the parts that fallaciously attribute the conclusion to a version of the AP.

But what if **A** is true? Will it be possible to do science in such a universe? Given what was just said, it is easy to see how a theory could be constructed so as to still be falsifiable. To do this, **B** must be replaced by the following.

(**B'**) It is possible, nevertheless, to posit a mechanism $\mathcal{X}$ by which the ensemble $\mathcal{M}$ was constructed, on the basis of which one can show that almost every universe in $\mathcal{M}$ has a property $\mathcal{W}$ with the following characteristics:³ (i) $\mathcal{W}$ does not follow from any known law of nature or observation, so it is consistent with everything we know that $\mathcal{W}$ could be false in our universe; (ii) there is a practical experiment that could show that $\mathcal{W}$ is not true in our universe.

If these conditions are satisfied, then an observation that $\mathcal{W}$ is false in our universe disproves **A** and **B'**. Since, by assumption, the experiment can be done, the theory based on these postulates is falsifiable.

Note that what would be falsified is only the specific **B'** dependent on a particular mechanism $\mathcal{X}$. Since $\mathcal{X}$, by generating the ensemble, will imply **A**, what is falsifiable is the postulate that the mechanism $\mathcal{X}$ acts in nature. Conversely, a mechanism that generates a random ensemble – as described by **B** rather than **B'** – cannot be falsified, as I will demonstrate below.

³ As discussed in Section 20.5, because of the issue of selection effects related to the existence of life, this can be weakened to *almost every universe in $\mathcal{E}$ that contains life also has property $\mathcal{W}$* .

Someone might argue that it is logically possible that **A** and **B** are true and that, if so, this would be bad only for those of us who insist on doing science the old-fashioned way. If an otherwise attractive theory points in the direction of **A** and **B**, then we should simply accept this and abandon what may be outmoded ideas about ‘how science works’.

If this is the case, then it will always be true that basic questions about our universe cannot be answered by any scientific theory (that is, by a theory that could be rationally argued on the basis of shared evidence to be true). But the fact that it is a possibility does not mean we should worry unduly about it turning out to be true. This is not the only hypothesis about the world that, if true, means that science must remain forever incomplete.

Others argue that it is sufficient to do science with one-way predictions of the following form: ‘Our theory has many solutions S_i . One of them, S_1 , gives rise to a prediction X . If X is found, that will confirm the combination of our theory and the particular solution S_1 . But belief in the theory is not diminished if X is not found, for there are a large number of solutions that do not predict X .’

One problem with this is that it can easily lead to a situation in which the scientific community is indefinitely split into groups that disagree on the likelihood that the theory is true, with no possible resolution. Indeed, it is plausible that this is already the case with string theory, which appears so far unfalsifiable but makes claims of this form. A second problem is that, even if X were found, another theory could be invented that also had a solution that predicted X . If neither were falsifiable, there would be no possibility of deciding which one was true.

Thus, so long as we prefer a science based on what can be rationally argued from shared evidence, there is an ethical imperative to examine only hypotheses that lead to falsifiable theories. If none is available, our job must be to invent some. So long as there are falsifiable – and not yet falsified – theories that account for the phenomena in question, the history of science teaches us to prefer them to their non-falsifiable rivals. Otherwise the process of science stops and further increases in knowledge are ruled out. There are many occasions in the history of science when this might have happened; we know more than people who espoused Ptolemy’s astronomy or Lysenko’s biology or Mach’s dismissal of atoms as forever unobservable, because at least some scientists preferred to go on examining falsifiable theories.

To deflate the temptation to proceed with non-falsifiable theories, it therefore suffices to demonstrate that falsifiable alternatives exist. In this chapter I review one falsifiable alternative to the AP, which is Cosmological

Natural Selection [13–17]. As it is falsifiable, it may very well be wrong. In Section 20.6, I will review this theory in light of developments made since it was first proposed. I will show that, in spite of several claims to the contrary, it has yet to be falsified. However, it remains falsifiable as it makes at least one prediction for a property $\mathcal{W}$ of the kind described in $\mathbf{B}'$. But whether it is right or wrong, the fact that a falsifiable theory exists is sufficient to show that the problems that motivate the AP might be genuinely solved by a falsifiable theory.

But if the AP cannot provide a scientific explanation, what are we to make of the claim that our universe is friendly to life? It is essential here to distinguish the different versions of the AP from what I would like to call ‘the anthropic observation’.

The anthropic observation Our universe is much more complex than most universes with the same laws but different values of the parameters of those laws. In particular, it has complex astrophysics, including galaxies and long-lived stars, and complex chemistry, including carbon chemistry. These necessary conditions for life are present in our universe as a consequence of the complexity which is made possible by the special values of the parameters.

I will describe this more specifically below. There is good evidence that the anthropic observation is true [6–9, 17] and why it is true is a puzzle that science must solve. However, to achieve this, it does not suffice just to restate what is to be explained as a principle, especially if the resulting theory is not falsifiable. One must discover a reason why it is true that has nothing to do with our own existence. Whether Cosmological Natural Selection is right or wrong, it does provide a genuine explanation for the anthropic observation. This is that the conditions for life, such as carbon chemistry and long-lived stars, serve another purpose, in that they contribute to the reproduction of the universe itself.

20.2 The problem of undetermined parameters

The second half of the twentieth century saw a great deal of progress in our understanding of elementary particle physics and cosmology. In both areas, Standard Models were established, which passed numerous experimental tests. In particle physics, the Standard Model – described in the mid 1970s – is based on two key insights. The first concerns the unification of the fundamental forces; the second considers why that unification does not prevent the various particles and forces from having different properties. The unifying

principle is that all forces are described in terms of gauge fields, based on making symmetries local. However, the symmetries between particles and among forces can be broken naturally when those gauge fields are coupled to matter fields. The Standard Model of cosmology took longer to establish, but is also based on the behaviour of matter fields when the symmetry breaks. In particular, this leads to the existence of a non-zero vacuum energy, which can both drive the inflation of the early universe and accelerate the expansion today.

In each case, however, there is a catch. The interactions of the gauge fields with each other and with gravity are determined completely by basic symmetries, whose description allows a very small number of parameters. However, the dynamics of the matter fields needed to realize the symmetry-breaking spontaneously and dynamically is arbitrary and requires a large number of parameters. This is because the easiest matter fields to work with are scalar fields, and no transformation properties constrain the form of their self-interactions.

The result is that the Standard Model of particle physics has more than twenty adjustable parameters. These include the masses of all the basic stable elementary particles (the proton, neutron, electron, muon, neutrino) and also the coupling constants and mixing angles associated with the various interactions. These are not determined by any principle or mechanism we know; they must be specified by hand to bring the theory into agreement with experiment. Similarly, the Standard Model of cosmology has about fifteen parameters.

One of the biggest mysteries of modern science, therefore, is how these thirty-five or so parameters are determined. There are two especially puzzling aspects to this problem. The first is the *naturality problem*. Many of the parameters, when expressed in terms of dimensionless ratios, are extremely tiny or extremely large. In Planck units, the proton and neutron masses are around 10^{-19} , the cosmological constant is 10^{-120} , the coupling constant for the self-interaction of the field responsible for inflation cannot be larger than 10^{-11} , etc.

The second puzzling aspect is the *complexity problem*. Our universe has an array of complex and non-equilibrium structures, spread out over a huge range of scales from clusters of galaxies to living cells. It is not too hard to see that this remarkable circumstance depends on the parameters being fine-tuned to lie within narrow windows. Were the neutron heavier by only 1%, the proton light by the same amount, the electron twice as massive, its electric charge 20% stronger or the neutrino as massive as the electron, there would be no stable nuclei, no stars and no chemistry. The universe would

be just hydrogen gas. The anthropic observation stated in the introduction is one way to state the complexity problem.

Despite all the progress in gauge theories, quantum gravity and string theory, not one of these problems has been solved. Not one mass or coupling constant of any particle considered now to be elementary has ever been explained by fundamental theory.

20.3 The failure of unification to solve the problem

For many decades there has been a consensus on how to solve the problems of the undetermined parameters: *unify the different forces and particles by increasing the symmetry of the theory and the number of parameters will decrease*. The expectation that unification reduces the number of parameters in a theory is partly due to historical experience. In several cases, unification has been accomplished by the discovery of a symmetry principle which relates things heretofore unconnected and reduces the number of parameters. This worked, for example, when Newton unified the theory of planetary orbits and when Maxwell showed that light was a consequence of the unification of electricity and magnetism. There is also the following philosophical argument: unification operates in the service of reductionism and this aims to provide a fundamental theory which will answer all possible questions and so cannot have free parameters.

Whatever the arguments for it, the correlation between unification and reduction in the number of parameters has not worked recently. Indeed, the last few times it was tried, it went the other way. One can reduce the number of parameters slightly by unifying all elementary particle physics in one Grand Unified Theory. However, one does not eliminate most of the freedom, because the values of the observed fundamental parameters are traded for the Higgs vacuum expectation values, which are not determined by any symmetry and remain free.

The grand unified theories had two problems. The first is that the simplest version of them, based on the group $SU(5)$, was falsified. It predicted that protons would decay with some minimum rate. The experiment was performed in the 1980s and protons were seen not to decay at that rate. This was the last time there was a significant experimental test of a new theoretical idea about elementary particles.

One can consider more complicated grand unified models, in which protons do not decay or the decay rate is much smaller. But all such models suffer from the second problem – their lack of naturalness. They require two Higgs scales, one at around 1 TeV and the other at around 10^{15} TeV. But

quantum corrections tend to pull the two scales closer to each other; to keep their ratio so large requires fine-tuning of the coupling constants of the theory to roughly one part in 10^{15} . To solve this problem, supersymmetry was proposed to relate bosons to fermions. One might think this would reduce the number of free parameters, but it goes the other way. The *simplest* supersymmetric extension of the Standard Model has 125 parameters.

Supersymmetry is a beautiful idea, and it was hard not to get very excited about it when it was first introduced. But so far it has to be counted as a disappointment. Had the addition of supersymmetry to what we know led to unique predictions (e.g. for what will be seen at the LHC), that would have been very compelling. The reality has turned out to be quite different. The problem is that, while supersymmetry is not precisely unfalsifiable, it is difficult to falsify, as many negative results can be – and have been – dealt with by changing the parameters of the theory. Supersymmetry would be completely convincing if there were even one pair, out of all the observed fundamental particles, that could be made into superpartners. Unfortunately, this is not the case, and one has to invent superpartners for each one of the presently observed particles.

This introduces a huge amount of arbitrariness. The current situation is that the minimal supersymmetric Standard Model has so much freedom, coming from its 125-dimensional parameter space, that – depending on which region of the parameter space one chooses – there are at least a dozen scenarios that could be probed by the upcoming LHC experiments [18]. Almost any result seen by the LHC could be – and probably will be – promoted as evidence for supersymmetry, whether or not it actually is. To test whether or not particle physics is supersymmetric will take much longer, as it will require measuring enough amplitudes to see if they are related by supersymmetry.

Another possible solution is to unify further the theory by coupling to gravity. There are two well developed approaches to quantum gravity – one non-perturbative, which means it makes no use of a background of classical spacetime, and the other perturbative, which describes small excitations of a classical spacetime. The latter includes loop quantum gravity, spin foam models, dynamical triangulations and others. In recent years, much progress has been made in these directions. Indeed, this has led to the realization that many models of this kind have emergent matter degrees of freedom [19, 20], whose properties are already fixed by the dynamics of the quantum spacetime. There is even a large class of models whose excitations include chiral states that match the properties of the Standard Model fermions [21, 22]. These recent results suggest that at the non-perturbative

level, quantum gravity theories are automatically unified with matter, are highly constrained and hence highly predictive and falsifiable.

The perturbative approach, which is string theory, makes very strong assumptions about how the string is to be quantized,⁴ and it also makes two physical assumptions: (1) that no matter on how small a scale one looks, space-time looks classical with small quantum excitations; (2) Lorentz invariance is a good symmetry up to infinite energies and boosts. It is not certain that both these assumptions can be realized consistently. After many years, there are only proofs of consistency and finiteness of perturbative string theory to second (non-trivial) order in perturbation theory, and attempts to go further have not so far succeeded.⁵ But these results indicate that the assumptions mentioned previously do put some constraints on particle physics. Supersymmetry is required, and the dimension of spacetime must be ten.

To the order of perturbation theory for which it is known to be consistent, string theory unifies all the interactions, including gravity. It was therefore originally hoped that it would be unique. These hopes were quickly dashed, and indeed the number of string theories for which there is evidence has been growing exponentially as string theorists have developed better techniques to construct them. Originally there were five consistent supersymmetric string theories in ten dimensions. But, the fact that the number of observed dimensions is four led to the hypothesis that the extra six dimensions are curled up very small or otherwise hidden from large-scale observations. Unfortunately, the number of ways to do this is quite large, at least 10^5 . In recent years, evidence has been found for many more string theories, which incorporate non-perturbative structures of various dimensions, called ‘branes’.

A key problem has been constructing string theories that agree with the astronomical evidence that the vacuum energy (or cosmological constant) is positive. The problem is that a positive cosmological constant is not consistent with supersymmetry. But supersymmetry appears to be necessary to cancel dramatic instabilities related to the existence of tachyons in the spectrum of string theories.

A few years ago, dramatic progress was made on this problem by Kachru and collaborators [25].⁶ They found a way round the problem by wrapping flux around cycles of the compactified 6-manifold and thereby discovered evidence for the existence of string theories with positive vacuum energy.

⁴ A recent paper by Thiemann [23] suggests that, with different technical assumptions, there are consistent string theories in any dimension without supersymmetry.

⁵ For details of precisely what has and has not been proven regarding string theory, loop quantum gravity and other approaches to quantum gravity, see ref. [24].

⁶ This built on earlier work by Giddings and colleagues [26], Bousso and Polchinski [27] and others.

This evidence is very weak – e.g. they are unable to construct propagation amplitudes even for free, non-interacting strings – but they are able to argue that there are consistent string theories with the desired characteristics. Their low-energy behaviour should be captured by solutions to classical supergravity, coupled to the patterns of the branes in question. They then construct the low-energy, classical, supergravity description.

Of course, the logic here is backwards. Had they been able to show that the required supergravity solutions do not exist, they would have ruled out the corresponding string theories. But the existence of a good low-energy limit is not a sufficient condition for a theory to exist. So, on logical grounds, the evidence for string theories with positive cosmological constant is very weak. However, if one takes the existence of these theories seriously, there is a disturbing consequence: the evidence suggests that the number of distinct theories is vast, of the order of 10^{100} to 10^{500} [28–30]. Each of these theories is consistent with the macroscopic world being 4-dimensional and with the existence of a positive and small vacuum energy. But they disagree about everything else; in particular, they imply different versions of particle physics, with different gauge groups, spectra of fermions and scalars and different parameters.

The fact that there are so many different ways to unify gauge fields, fermions and gravity consistently makes it likely⁷ that *string theory will never make any new, testable predictions about elementary particles*.⁸ Of course, a very small proportion of the theories will be consistent with current particle physics data. But even if this is only one in 10^{450} , there will still be 10^{50} viable theories. Although some of these may be disproved by some future experiment at higher energy, the number is so vast that it appears likely that, whatever is found, there will be many versions of string theory that agree with it.

20.4 Mechanisms for production of universes

Whatever the fate of the positive vacuum energy solutions of string theory, one thing is clear. At least up till now, the hope that unification would

⁷ It should be noted that, while some string theorists have argued that this situation calls for some version of the AP [28], others have sought ways to pull falsifiable predictions from the theory [29,30].

⁸ It may be claimed that string theory makes a small number of correct *postdictions*, e.g. that there are fermions, gauge fields, gravitational fields and no more than ten spacetime dimensions. But this is not itself a strong argument for string theory, as there are other approaches to unifying gravity with quantum theory and the Standard Model for which non-trivial properties have also been proven [24]. So there is no evidence that string theory is the unique theory that unifies gravity with the Standard Model.

lead to a unique theory has failed dramatically. So it seems unlikely that the problem of accounting for the values of the parameters of the Standard Models of particle physics and cosmology will be solved by restrictions coming from the consistency of a unified theory.

The rest of this chapter is devoted to alternative explanations of the choice of parameters. All alternatives I am aware of involve the postulate **A** given in Section 20.1. They also require the further postulate **C**.

- (**C**) There are many possible consistent phenomenological descriptions of particle physics at scales much less than the Planck energy. These may correspond to different phases of the vacuum or different theories altogether.

As a result, fundamental physics is assumed to give us, not a single theory, but a space of theories, $\mathcal{L}$, which has been called the *landscape* [14–17].⁹ As in biology, we distinguish the space of genotypes from the space of phenotypes, i.e. we distinguish $\mathcal{L}$ from the space of the parameters of the Standard Model $\mathcal{P}$. All multiverse theories then make some version of the ‘multiverse hypothesis’.

Multiverse hypothesis. Assuming **A** and **C**, the whole of reality – which we call the multiverse – consists of many different regions of spacetime, within which phenomena are governed by different phenomenological descriptions. For simplicity, we call these ‘universes’.

The multiverse is then described by probability distributions ρ_L in $\mathcal{L}$ and ρ_P in $\mathcal{P}$. These describe the population of universes within the ensemble. Multiverse theories can be classified by their answers to the following questions.

- (i) How is the ensemble of universes generated?
- (ii) What mechanism produces the probability distribution ρ_P ?
- (iii) What methodology is used to produce predictions for our universe from the ensemble of universes?

We are interested here only in those multiverse theories that make falsifiable predictions. To do this, the ensemble of universes cannot be arbitrarily specified. Otherwise it could be adjusted to agree with any observations by making a typical universe agree with whatever is observed about ours. To have empirical content, the ensemble of universes must be generated by

⁹ It should be mentioned that the word ‘landscape’ was chosen in refs. [14]–[17] to make the transition to the concept of *fitness landscape* – well known in evolutionary theory – more transparent.

some dynamical mechanism which is a consequence of general laws. The properties of the ensemble are then determined by laws that have other consequences which can – at least in principle – be checked independently. Two mechanisms for the generation of universes have been studied: eternal inflation and bouncing black hole singularities. We will describe each of these and then contrast their properties.

20.4.1 *Eternal inflation*

The inflation hypothesis provides a plausible explanation of several observed features of our universe, such as its homogeneity and uniformity [31–34]. The basic idea is that, at very early times, the energy density is dominated by a large vacuum energy, possibly coming from the vacuum expectation value of a scalar field. As the universe expands exponentially due to this vacuum energy, the vacuum expectation value also evolves in its potential. Inflation comes to an end when a local minimum of the potential is reached, converting vacuum energy into thermal energy that is presumed to become the observed cosmic microwave background.

The model appears to be consistent, assuming all scales involved are less than the Planck scale, and has made predictions which have been confirmed.¹⁰ But there are problems. Some have to do with the initial conditions necessary for inflation. It has been shown that a region of spacetime will begin to inflate if the vacuum energy dominates other sources and if the matter and gravitational fields are homogeneous to good approximation over that region. Of course, we do not know the initial conditions for our universe, and we have observed nothing so far of the conditions prior to inflation. But on several plausible hypotheses about the initial state, the conditions required for a region to begin inflating are improbable. For example, the existence of inflation and the smallness of the associated density fluctuations, $\delta\rho/\rho$, requires that the self-coupling of the inflaton be small.

However, once the conditions necessary for inflation are met, it appears likely in some models that inflation does not happen just once. Because of quantum fluctuations, the scalar field will sometimes fluctuate ‘up’ the potential, so that even after inflation has ended in one region, it will continue in others. This can lead to the scenario known as *eternal inflation* [41–45], in which there are always regions which continue to inflate. There is then a competition between the classical force from the potential, causing the expectation value to decrease or ‘roll’ towards a local minimum, and the

¹⁰ However, it should be noted that other theories make predictions so far indistinguishable from those of inflation [35–40].

quantum fluctuations, which can lead it to increase locally. Given plausible – but not necessary – assumptions, this can result in the creation of a large, or even infinite, number of regions which locally resemble ordinary FRW universes.

20.4.2 *Bouncing black hole singularities*

A second mechanism for generating new universes is through the formation of black holes. It is known that a collapsing star, such as the remnant of a supernova, will form either a neutron star or a black hole, depending on its mass. There is an upper mass limit for a stable neutron star. Remnants of supernovae larger than this have nothing to restrain them from collapsing to the point at which an event horizon is formed. Rough estimates of this upper mass limit are between 1.5 and $2.5M_{\odot}$.

According to the singularity theorem of Penrose, proved on general assumptions, classical general relativity predicts the formation of a singularity at which the curvature of spacetime becomes infinite and spacetime ends. No trajectory of a particle or photon can be continued past the singularity to the future.

This result, however, may be modified by quantum effects. Before the singularity is reached, densities and curvatures reach the Planck scale and quantum gravity dictates the dynamics. As early as the 1960s, pioneers of this field, such as John Wheeler and Bryce deWitt, conjectured that the effects of quantum gravity would reverse the collapse, removing the singularity and causing the matter that was collapsing to expand [46]. Time then does not end and there is a region of spacetime to the future of where the singularity would have been. The result is the creation of a new expanding region of spacetime, which may grow and become, for all practical purposes, a new universe. This region is inaccessible from the region where the black hole originally formed. The horizon is still there, which means that no light can escape from the new region to the previous universe. Unless the black hole evaporates, the causal structure implies that every event in the new region is to the future of every event in the region of spacetime where the black hole formed.

The transition by which collapse to a singularity is replaced by a new expanding region of spacetime is called a ‘bounce’. One can then hypothesize that our own big bang is the outcome of a collapse in a previous universe and that every black hole in our universe is giving rise to a new universe.

The conjecture that singularities in classical general relativity are replaced by bounces has been investigated and confirmed in many semi-classical

calculations (see, for example, ref. [48]). It is also suggested by some calculations in string theory [49, 50]. In recent years, quantum gravity theory has been developed to the point where the conjecture can be investigated exactly. It has been shown that cosmological singularities do bounce [51–55]. Assuming that the theory of quantum gravity is correct, this means that the big bang in our past could not have been the first moment of time; there must have been something before that. Recent results from models of black hole interiors also strongly support the conjecture that black hole singularities are replaced by bounces [56–58]. These results strengthen the conjecture that quantum gravity effects replace black hole singularities with the birth of new universes.

20.4.3 Comparison of universe-generation mechanisms

In comparing these mechanisms for the reproduction of universes, several issues should be borne in mind.

How reliable is the evidence for the mode of production of universes?

We know that our universe contains black holes. There is observational evidence that many galaxies have large black holes at their centres. They are also believed to form from some supernova explosions, and there may be around 10^{18} such black holes in the observable universe. A number of candidates for such stellar black holes have been found, and the evidence so far, e.g. from studying X-rays from their accretion disks, supports their identification as black holes.

There has been speculation that many black holes may have been created by strong inhomogeneities in the early universe. However, the simplest theories of inflation predict that inhomogeneities were not strong enough to create many such primordial black holes. In any case, were they there, one would expect to see signals of their final evaporation, and no such signals have been detected. Thus, it is likely that the population of black holes is dominated, numerically, by supernova remnants.

We also have reasonable, if not yet compelling, theoretical evidence that black holes bounce [48–50], as well as exact quantum calculation results showing that there was something to the past of our big bang [51–55]. Thus there is plausible evidence that our universe is creating new universes through the mechanism of black hole production and that our own universe was created by such a process.

By contrast, the formation process for new universes in eternal inflation cannot be observed, since it takes place outside of our past horizon. The

existence of the process depends entirely on believing in particular inflationary models that lead to eternal inflation. While many do, it is also possible to invent inflationary models that do not. For although there is evidence for inflation in general, several predictions of inflation having been confirmed, the observations do not yet discriminate between models that do and do not predict eternal inflation.

Also, some of the calculations backing up the eternal inflation scenario use very rough methods, based on imprecise theories employing semi-classical estimates for ‘the wave-function of the universe’. This is a speculative extension of quantum theory to cosmology which has not been put on firm ground, conceptually or mathematically. Very recently, progress has been made in quantum cosmology which allows precise predictions to be made from a rigorous framework [51–55]. However, while inflation has been studied with these methods, so far the results do not address the conjectures that underlie eternal inflation.

Other approaches to eternal inflation [41] rely only on quantum field theory in curved spacetime. This is better understood, but there are still open questions about its applicability for cosmology. As a consequence, eternal inflation can be considered an interesting speculation, but it is supported by neither observation nor firm mathematical results within a well defined theory of quantum gravity.

What physics is involved in the mechanism of reproduction of universes?

The physical scale governing the birth of universes in eternal inflation is the scale of the inflaton potential in the regime where nucleation of new inflating regions takes place. This is at least the grand unified scale $\sim 10^{15}$ GeV and could be as large as the Planck scale. We have theories about the physics at this scale, but so far no predictions made by these theories have been confirmed experimentally. In fact, the only relevant experimental evidence, coming from proton decay experiments, falsified the simplest grand unified theories.

By contrast, the physical scale that governs black hole production is that of ordinary physics and chemistry. How many stars are massive enough to form supernovae is determined by ordinary chemical processes that govern the formation and cooling of giant molecular clouds. We know the physics of stars and supernovae reasonably well, and knowledge is improving all the time due to progress in theory, observation and experiment. Thus, we understand the physics that controls how many universes are created through black hole formation and we have speculations – but no detailed

understanding – of the processes that govern the creation of new universes in eternal inflation.

What is the structure of the multiverse predicted by each theory?

A multiverse formed by black hole bouncing looks like a family tree. Each universe has an ancestor, which is another universe. Our universe has at least 10^{18} children; if they are like ours, they each have roughly the same number of children. The structure of a multiverse formed by eternal inflation is much simpler. Each universe has the same ancestor, which is the primordial vacuum. Universes themselves have no descendants.

20.5 Varieties of anthropic reasoning

Just as there are two modes of production of universes, there are two modes of explanation by which people have tried to draw physical predictions from multiverse models. These are the Anthropic Principle (AP) and Cosmological Natural Selection (CNS). There are actually several different anthropic principles and several different ways that people draw conclusions from them. We discuss the major ones in this section, including the arguments of Dicke, Hoyle and Weinberg that are usually cited as successes of the AP.¹¹ We consider CNS in Section 20.6.

20.5.1 The theological anthropic principle

It is not surprising that some theologians and scientists take the *complexity* problem as evidence that our universe was created by a benevolent God. They argue that if the best efforts of science lead to an understanding of the laws of nature within which there is choice, and if the choices that lead to a universe with intelligent life are extremely improbable, the very fact that such an improbable choice was made is evidence for intention. This is the old argument from design, recycled from controversies over evolution theory. It should be admitted that it does have force; the discovery of a craft as complex as an airbus on a newly discovered planet would be good evidence for intelligent life there. But this argument has force only so long as there are no plausible alternative explanations for how the choice might have been made. In the case of biology, natural selection provides a falsifiable and so far successful explanation, which renders unnecessary the argument from design.

¹¹ I do not use the traditional nomenclature of ‘weak’ and ‘strong’ anthropic principles, as these terms have been used in different ways by different authors.

We can learn from the long history of the controversy in biology what tests a proposed explanation must satisfy if it is to be more convincing than the argument for intentional creation of a biofriendly universe.

- There must be a physical mechanism which converts the improbable to the probable, i.e. that raises the probability that a universe such as ours was chosen from infinitesimal to order unity.
- That mechanism must be falsifiable. It must be built from processes or components which can be examined empirically and be seen to function as hypothesized, either by being created in a laboratory or by occurring in nature in our observable universe.

We will see below that these tests are not satisfied by the different versions of the AP used in physics and cosmology. We will then propose a way of reasoning about multiverses that is not anthropic but does satisfy these tests.

20.5.2 Selection effects within one universe

The first anthropic arguments in cosmology were based on the use of *selection effects* within our observable universe. A selection effect is an effect due to the conditions of observation, which must be applied to a set of observations before they can be interpreted properly. A classical example is the following. Early humans observed that all around them was land and water, and above them was sky. From this, they deduced that our universe consists of a vast continent of land, surrounded by water and covered by sky. They were wrong; the reason was that they forgot to take into account the fact that the conditions they observed were necessary for them to exist as intelligent mammals. We now know that our universe is vastly bigger than they imagined and that most of it is filled with nothing but a very dilute gas and radiation. If we picked a point randomly, it would be very unlikely to be on the surface of a planet. But the conditions necessary for our evolution turn the improbable into the probable.

Dicke [59] used this logic to debunk Dirac's 'law of large numbers'. Dirac observed a coincidence [60] between the age of our universe and the proton mass in Planck units (the former is roughly the inverse cube of the latter). He argued that this requires an explanation and proposed one in which the gravitational constant G (and hence the Planck unit) would change in time. Dicke pointed out that the coincidence could be explained by our own existence, without invoking such a variation. Intelligent life requires

billions of years of evolution on the surface of a planet near a stable long-lived star, and he was able to argue that the physics of stars implies that these conditions would only hold at an era where Dirac's coincidence was observed. Indeed, there is still no evidence for the variation of G postulated by Dirac. This argument is logically sound, but is quite different from the other types of explanation discussed below.

20.5.3 False uses of the Anthropic Principle

There are other successful arguments which have been called 'anthropic', although they have nothing to do with selection effects or the existence of life. An illustrative example is Hoyle's prediction of a certain resonance in the nuclei of carbon [61]. Hoyle argued that for life to exist there must be carbon. Carbon is indeed plentiful in our universe and must have been made either during the big bang or in stars, as these are the only ways to synthesize copious amounts of chemical elements. Detailed studies show that it could not have been made in the big bang, so it must have been made in stars. Hoyle argued that carbon could only be formed in stars if there were a certain resonant state in carbon nuclei. He communicated this prediction to a group of experimentalists who went on to find this resonant state.

The success of Hoyle's prediction is sometimes used as support for the effectiveness of the AP. However, it has nothing whatsoever to do with the existence of life because the first step of his argument is unnecessary. The fact that we – or other living things – are made of carbon is totally unnecessary to the argument. Indeed, were there intelligent life-forms which evolved without carbon chemistry, they could just as easily make Hoyle's argument.

To be clear why Hoyle's argument does not employ the AP, let us examine its logical schema and then ask which step we would have to question were the prediction falsified. The key steps in the argument are as follows.

- (i) X is necessary for life to exist.
- (ii) X is true about our universe.
- (iii) Using the laws of physics, as presently understood, together with other observed facts Y , we deduce that if X is true of our universe, then so is Z .
- (iv) We therefore predict that Z is true.

In Hoyle's case, X is the statement that our universe is full of carbon, Y is the claim that this could only be made in stars, and Z is the existence of a certain resonance in carbon.

It is clear that the prediction of Z at step (iii) in no way depends on step (i). To see this, ask how we would react if Z were found not to be true. Our only option would be to question either Y or the deduction from the presently known laws of physics of Z . We might conclude that the deduction was wrong, for example, if we made a mistake in a calculation. If no such option worked, we might have to conclude that the laws of physics have to be modified. But we would never question (i), because – while true – it plays no role in the logic of the argument leading to the prediction for Z .

There are other examples of this kind of mistaken reasoning, in which an argument promoted as ‘anthropic’ actually has nothing to do with the existence of life, but is instead a straightforward deduction from observed facts.

20.5.4 Selection effects within a multiverse

More recent arguments termed ‘anthropic’ are made within the context of multiverse scenarios. It is tricky to pull falsifiable predictions from such scenarios, because (so far) we have only observed one member of the ensemble. But it is not impossible, as I will show shortly.

First, however, we have to dispose of mistaken uses of multiverse selection effects. These are arguments in which point (i) in the above schema for Hoyle’s argument is replaced as follows.

- (i)’ We live in one member of a multiverse in which the laws of physics vary.
 X is necessary for life, so by a selection effect we must live in a universe in which X is true.

The other steps in Hoyle’s argument remain the same. The substitution of (i)’ for (i) has not changed the logic of the argument; (i)’ is as irrelevant for the argument as (i) was, because (ii) still does the real logical work. Furthermore, if the prediction Z were falsified, we would not question (i)’. Rather, the problem would be to understand why, *in one universe*, X is true without Z being true. This problem must be solved within one universe and is independent of whether or not the universe we live in is part of a multiverse. Had the carbon resonance lines which Hoyle predicted not been found, he would neither have questioned the existence of life nor regarded the result as relevant to the number of universes. Instead, given that carbon is plentiful, he would have examined all the steps in the argument, looking for a loophole. This might have involved exotic new sources of carbon, such as collisions of neutron stars.

Hence, to pull a genuinely falsifiable prediction from a multiverse theory, which genuinely depends intrinsically on the hypothesis that our universe is

part of a multiverse, the logic must be different from the schema just given. One way to do this is to fix a multiverse theory $\mathcal{T}$ which gives rise to an ensemble of universes $\mathcal{M}$. We are interested in predictions concerning some set of properties p_i , where i labels the property. The theory may give some *a priori* probability $\rho_{\mathcal{M}}(i)$ that a universe picked randomly from the ensemble will have property i .

To make the argument precise, we will need to refer to another ensemble which consists of randomly generated universes $\mathcal{R}$. This is produced by taking properties allowed to vary within the theory and selecting their values randomly, according to some measure on the parameter space of the theory. By ‘random’ we mean that the measure chosen is unbiased with respect to the choice of hypothesis for the physical mechanism that might have produced the ensemble. For example, if we are interested in string theory, we randomly pick universes with different string vacua. The difference between $\mathcal{R}$ and $\mathcal{M}$ is that the former is picked randomly from the physically possible universes, whereas the latter is generated dynamically, by a mechanism prescribed in theory $\mathcal{T}$.

Before comparing this with our universe, we should take into account that we may not live in a typical member of the ensemble $\mathcal{M}$. There will be a sub-ensemble $\mathcal{LM} \subset \mathcal{M}$ of universes that have the conditions for intelligent life to exist. Depending on the theory, the probability for a random universe in $\mathcal{M}$ to also be in $\mathcal{LM}$ may be very small or close to unity. But we already know that, if the theory is true, we are in a universe in $\mathcal{LM}$. So we should compute $\rho_{\mathcal{L}}(i)$, the probability that a universe randomly picked in the sub-ensemble $\mathcal{L}$ contains property p_i . Similarly, there will be a sub-ensemble $\mathcal{LR} \subset \mathcal{R}$ of those universes within the random ensemble which contain life.

The theory, then, can only make a falsifiable prediction if some restrictions are satisfied. It is no good considering properties that depend on the conditions necessary for life, for they will always be satisfied in a universe where life exists. To find a falsifiable prediction, the following must hold.

- There is a property $\mathcal{B}$ which is independent of the existence of life, i.e. it must be physically and logically possible that universes exist which have life but do not have $\mathcal{B}$. To make this meaningful, we must refer to the ensemble $\mathcal{R}$ of random universes. The probability of a universe in $\mathcal{LR}$ having property $\mathcal{B}$ must be small.
- Within the ensemble $\mathcal{M}$ generated by theory $\mathcal{T}$, there must be a strong correlation between universes with life and those with property $\mathcal{B}$.

- The argument will have force if the property $\mathcal{B}$ has not yet been looked for, so that this property is a genuine prediction of the theory $\mathcal{T}$, vulnerable to falsification at the time the prediction is made.

Under these conditions, we can now proceed to do real science with a multiverse theory. We make the assumption that our universe is a typical member of the ensemble $\mathcal{L}$. We then look for property $\mathcal{B}$. The theory is falsifiable because, if property $\mathcal{B}$ is not seen in our universe, then we know that theory $\mathcal{T}$ which gave rise to the ensemble $\mathcal{L}$ is false. If, however, $\mathcal{B}$ is found, then the evidence favours the ensemble $\mathcal{M}$ produced by the theory over the random ensemble $\mathcal{R}$.

We can draw a very important conclusion from this. To make a falsifiable prediction, a theory must produce an ensemble $\mathcal{M}$ that differs from a random ensemble $\mathcal{R}$. There must be properties that are improbable in $\mathcal{LR}$ and probable in $\mathcal{LM}$. If the two ensembles are identical, and if there is a high probability that a universe with life in $\mathcal{M}$ has property $\mathcal{B}$, this is also true of a universe with life in a randomly generated ensemble. There are two problems with this. First, the particular hypotheses that make up the theory $\mathcal{T}$ are not being tested, for they are empirically equivalent to a random number generator. Second, and more importantly, without the random ensemble, we cannot give meaning to the necessary condition that $\mathcal{B}$ is uncorrelated with the conditions necessary for life. For the observation of $\mathcal{B}$ to be able to falsify $\mathcal{T}$, it must be possible that there exist ensembles in which the probability of $\mathcal{B}$ in universes with life is low. The operational meaning of this is that they are uncorrelated in an ensemble of randomly generated universes.

To put this more strongly, suppose that a theory $\mathcal{T}$ generates an ensemble whose living sub-ensemble $\mathcal{LM}$ is identical to the living sub-ensemble of the random ensemble. Assume this theory predicts a property $\mathcal{B}$ which has probability close to unity in $\mathcal{LM}$. If $\mathcal{B}$ is observed, that does not provide evidence for $\mathcal{T}$, because there is already a complete correlation between $\mathcal{B}$ and life in the ensemble of randomly generated universes.

The conclusion is that no multiverse theory that produces an ensemble identical to $\mathcal{R}$ can give falsifiable predictions. Genuine falsifiable predictions can only be made by a theory whose ensemble $\mathcal{M}$ differs from $\mathcal{R}$. Furthermore, to give a genuine prediction, there must be a property $\mathcal{B}$, not yet observed but observable with present technology, which is probable in $\mathcal{LM}$ but improbable in $\mathcal{LR}$.

A very important consequence of this follows from the following observation: *properties of the ensemble $\mathcal{M}$ generated by a mechanism in a theory $\mathcal{T}$ will be random if that property concerns physics on a scale many orders*

of magnitude different from the scale of the mechanism of production of universes defined by $\mathcal{T}$. One reason is familiar from statistical mechanics. Ensembles tend to be randomized in observables that are not controlled in their definition. For example, for a gas in a room, the properties of individual atoms are randomized, subject only to their random values being related to the temperature and density in the room.

A second reason has to do with a general property of local field theories, namely the decoupling of scales. In renormalizable field theories, including those of the Standard Model, there is only weak coupling between modes of the field at very different scales. We can see this applied to eternal inflation models. The mechanism for generating universes involves quantum fluctuations in the presence of a vacuum condensate with energy between 10^{15} and 10^{20} GeV. Properties of the vacuum that influence physics at those scales will play a role in determining the ensemble of universes created. If we consider the space of possible theories (perhaps string vacua), these will be preferentially selected by properties that strongly influence the probability for a quantum fluctuation in this environment to be uniform. These will include coupling constants for interactions manifest on that scale and vacuum expectation values for Higgs fields on that scale. But the exact values of masses or couplings many orders of magnitude lighter are not going to show up.

What will matter is the total number of degrees of freedom, but all particles so far observed are many orders of magnitude lighter and may be treated as massless from the point of view of the physics of the creation of our universe. Hence, changes in the proton–neutron mass difference, or the electron–proton mass ratio, are not going to have a significant influence on the probability for universe creation. The result is that these properties will be randomized in the ensemble $\mathcal{M}$ created by eternal inflation.

As a result, it is reasonable to expect that any Standard Model parameters that govern low-energy (but not grand unification) physics will have the same distribution in $\mathcal{M}$ as in the random ensemble $\mathcal{R}$. These include the masses of the quarks, leptons and neutrinos, and the scale of electroweak symmetry-breaking (i.e. the weak interactions). It follows that *eternal inflation will not be able to make any falsifiable predictions about any low-energy parameters of the Standard Model of particle physics. Consequently, no solution to the complexity problem can come from eternal inflation, since that involves the values of these parameters.*

Eternal inflation may be able to make some predictions, but only those restricted to parameters that govern physics at grand unified scales. However, there are claims that eternal inflation – in conjunction with another

AQ: Please check spelling

principle – does lead to predictions about the cosmological constant [62–66] and we examine these next.

20.5.5 The Principle of Mediocrity

A variant of selection effects applied to a multiverse is the ‘Principle of Mediocrity’ (PM). This is defined by Garriga and Vilenkin [63] as requiring that ‘our civilization is typical in the ensemble of all civilizations in the universe’. This means that we weigh the ensemble $\mathcal{M}$ by the number of civilizations in each universe. It follows that all universes outside of $\mathcal{LM}$ have zero weight and that universes with more civilizations are weighed more heavily.

This principle adds several layers of presently untestable assumptions to the analysis. We know nothing reliable about the conditions that generate civilizations. While we can speculate, our genuine knowledge about this is unlikely to improve in the near future. If we conjecture that the number of civilizations will be proportional to the number of spiral galaxies, we can provisionally take the PM to mean that we weigh our ensemble with the number of spiral galaxies in each universe. Alternatively, we can postulate that the number of civilizations is proportional to the fraction of baryons that end up in galaxies [67, 68].

Garriga and Vilenkin then argue that certain predictions can be drawn concerning properties of the vacuum energy [63]. We note that, in conformity with the above argument, no predictions are drawn concerning properties that have to do with the parameters of low-energy physics and are uncorrelated in a random ensemble with the existence of life. Still, it is good that people put predictions on the table and we should take them seriously. To do so, we must ask what exactly would be falsified if one or more of their predictions were found to disagree with observation. The argument depends on properties of the eternal inflation theory, some rough guesses about the wave-function of the universe and how to reason with it, and some rationale about the effects of vacuum energy on the creation and evolution of galaxies.

The PM can only have force if it is more stable than the other parts of the argument leading to the predictions. Otherwise a falsification of the prediction may teach us only that the PM is unreliable. To be useful, a methodological principle must be reliable enough that it can be taken as firm and used as part of an argument to negate any hypothesis about physics.

So, is the PM on firmer ground than quantum cosmology or the theory of galaxy formation? I know of no *a priori* argument for the PM. If the multiverse is real, we may indeed live in a universe with the maximal number

of civilizations. But it could just as easily be false. There is no reason why we may not live in a universe which is atypical, in that it has some civilizations, but many fewer than other members of the ensemble. Thus, while we can argue for taking into account selection effects coming from the fact that we are in a universe hospitable to life, the PM is on much less firm ground.

The PM is sometimes supported by referring to ensembles within which we are typical individuals. Indeed, there are many ensembles within which this is the case. The problem is that there are also many ensembles with respect to which we are atypical. The PM has little force in human affairs, because – without further specification – it is vacuous, as we are both typical and atypical, depending on what ensembles we are compared against. To see this, let us ask some questions about how typical we are.

- (i) Do we live in the universe with the largest number of civilizations?
- (ii) Do we live in the universe with the largest number of intelligent beings?
- (iii) Do we live in the universe with the largest number of conscious minds?
- (iv) Do we live on the planet with the largest number of intelligent beings?
- (v) Do we live in the most populous city on my planet?
- (vi) Do we live in the most populous country on my planet?
- (vii) Are we members of the largest ethnic group on my planet?
- (viii) Do we have a typical level of wealth or income on my planet?
- (ix) Do we live at a time when more people are alive than at any other?

The answer to questions (i) to (iv) is that there is no way of telling with either present data or any conceivable future data. In my particular case, the answers to questions (v) to (viii) are no, but I know people who can answer yes to one or more of them. Question (ix) is ambiguous. If the ensemble includes all times in the past, the answer is probably yes. If it includes all times in future as well, it is impossible to know the answer.

Given how often any individual fails to be typical in ensembles we know about, it seems to me we are on equally weak ground reasoning from any assertion of answers to (i) to (iv) as we would be reasoning from (v) to (ix). I conclude that the PM is too ambiguous to be useful. It must be supplemented by a specification of the ensemble. When that is done, we can test it, but it is still found to be unreliable. Thus it must be even less reliable in situations where it cannot be tested.

The well known ‘doomsday argument’ [69–71] illustrates the perils of the use of the PM. Someone begins it by stating ‘I am a typical human being’. They may support that by noting the existence of some ensembles within which they are typical. Then they introduce a new ensemble $\mathcal{H}$, consisting

of all human beings who will ever live. They next assert that, since they are generally typical, they should be typical in that ensemble. They then draw the drastic deduction (which we call $\mathcal{C}$) that *roughly the same number of human beings will live after them as before*. Given that the population has been growing exponentially for a long time, this leads to the conclusion that the population should begin to fall drastically within their lifetime.

There are more details, but we do not need them to see the ways in which the argument is fallacious.¹² The ensemble $\mathcal{H}$ contains an unknown number of human beings, who may live in the future. There is no way, given any information we have at present, to determine if we (living now) are in any way typical or untypical members of $\mathcal{H}$. There is simply no point in guessing. Whether we who have lived so far constitute most of $\mathcal{H}$, an infinitesimal fraction of $\mathcal{H}$ or something in between, depends on events that will take place in the future, most of which we are unable to control, let alone predict.¹³ So it is simply impossible with current knowledge to deduce the truth value of $\mathcal{C}$.

However, we can still look to the past. The population has been growing exponentially for at least 10 000 years. Any person living in the last 10 000 years would have had just as much rational basis for following the reasoning from ‘I am a typical human being’ to conclusion $\mathcal{C}$ as we have. Other facts, such as the existence of weapons of mass destruction or global warming, are irrelevant, as they are not used to support $\mathcal{C}$. (The whole point of the argument is supposed to be that it is independent of facts such as these.)

But would a person have been correct to use this argument to conclude $\mathcal{C}$ a 1000 years ago? Clearly not; they would have been wrong because already many more people have lived since them than had lived before. But $\mathcal{C}$ is supposed to be a consequence of the PM. The conclusion is that there are two cases of individuals to which the PM may be applied. There is a class of

¹² Another criticism of the argument, from F. Markopoulou (personal communication), is that even to state that a person is typical in the ensemble $\mathcal{H}$ with respect to a given property is to assume that there is a normalizable probability distribution for that property in $\mathcal{H}$. If the property is birth order, then the normalizability of the probability distribution already implies that the population must decrease at some point in the future. Thus, the argument assumes what it claims to demonstrate. The only open issue is when this decrease occurs, but, as we see, this cannot in any case be determined by the argument.

¹³ It would take us too far afield to analyze why such a fallacious argument is so attractive. It has something to do with the fallacy that every statement that will, at the end of time, have a truth value, has a truth value now. The statement ‘I am a typical member of the ensemble $\mathcal{H}$ ’ is one that can only be given a truth value by someone in the unhappy situation of knowing they are the last of us, and they would thus judge it false. No one for whom the statement is true could possibly have enough information to ascribe to it a truth value, for the simple reason that to do so would require knowledge of the future. Thus, logic in this case cannot be Boolean because different observers, at different times, can only make partial judgments as to the truth values of propositions that concern themselves. A more adequate logic is that given by Heyting, which is intimately related to the causal relations amongst events in time [72].

individuals to whom the truth value of $\mathcal{C}$ – and hence of the PM – cannot be checked. Then there is a class of individuals about whom the truth value of $\mathcal{C}$ can be determined. In each and every one of these cases, $\mathcal{C}$ is false. Thus, in every case in which there is an independent check of the consequences of the PM, it turns out to be false. Hence, it is either false or undetermined. Hence there is no evidence for its truth.

20.5.6 Weinberg’s argument for the cosmological constant

Recently it has been claimed that the AP, and more specifically the PM, lead to a successful prediction. This is Weinberg’s prediction for the value of the cosmological constant Λ , first made in ref. [65] and then elaborated in refs. [66–68]. It is important to note that Weinberg and collaborators make two separate arguments. The first is the following: assuming **A** and **B**, we cannot find ourselves in a universe with too positive a Λ else galaxies would never have formed. The upper limit for Λ predicted by this argument – with all other constants of nature fixed – is about 200 times the present matter density [67] (baryons plus dark matter), which yields roughly $\Omega_\Lambda < 100$. This is about two orders of magnitude larger than the present observed value.

In their second argument, Weinberg and his collaborators attempt to improve this estimate by evoking the PM in the form just discussed. They find that the probability of finding Ω_Λ less than 0.7 is either 5% or 12%, depending on technical assumptions made. Thus one can conclude that, while the actual observed value is somewhat low compared to the mean, it is not unreasonable to argue that the observed value is consistent with the result of the analysis based on the PM.

It might be argued that there is something wrong with my case against the PM; since Weinberg’s first paper preceded the supernova and CMB measurements of Λ , his use of the PM has to count as a successful prediction. Indeed, this is perhaps the only successful new prediction in fundamental physics for the value of a physical parameter in decades.¹⁴

To reply, let us first distinguish the two arguments. One can reasonably conclude that Weinberg’s first argument is, in part, correct. Were $\Omega_\Lambda > 100$ (with all other constants of nature fixed), we would have a problem understanding why we live in a universe filled with galaxies. However, this is false use of the AP, of the kind discussed in Section 20.5.4, because the problem

¹⁴ It is sometimes stated that Weinberg made the only correct prediction for the order of magnitude of the cosmological constant, but a correct prediction was also made by Sorkin and colleagues [73], based on the causal set approach to quantum gravity.

has nothing to do with our own existence. Just as Hoyle's argument has nothing to do with life, but is only based on the observed fact that carbon is plentiful, so Weinberg's first argument only has to do with the fact that galaxies are plentiful. It could be made by a robot or disembodied spirit. Were $\Omega_\Lambda > 100$ (with all other constants fixed), there would be a contradiction between present models of structure formation, which are based on established physical principles, and the observation that our universe is filled with galaxies.

The first argument of Weinberg is sometimes presented as an example of the success of a selection principle within a multiverse. But it then follows the schema given at the beginning of Section 20.5.3, with X now being the existence of many galaxies and Z the requirement that $\Omega_\Lambda < 100$. Were $\Omega_\Lambda = 1000$, the problem would not be with the multiverse hypothesis. Rather, it would be to explain how galaxy formation happened *in a single universe* despite such a large Λ . Therefore, Weinberg's first argument is partly valid, but the part that is correct is just a rational deduction from the fact that there are galaxies. The existence of life and selection effects in a multiverse are completely irrelevant to the argument, as they can be removed from the argument without its logical force being in any way diminished.

Before considering the second argument, there is a caveat to deal with, which is the restriction to a class of universes in which all the other constants of nature are fixed. As pointed out by Rees [74, 75], Tegmark and Rees [76] and Graesser and colleagues [77], it is difficult to justify any claim to make a valid prediction based on this restricted assumption. One should instead consider ensembles in which other cosmological parameters are allowed to vary. When one does this, the constraint on Λ from Weinberg's first argument is considerably weakened. The above authors show this by considering the case of the magnitude of the density fluctuations, usually denoted Q , which is observed to be about 10^{-5} . One can argue that, holding Λ fixed, Q cannot be much more than an order of magnitude larger, for similar reasons. But, as they show, one can have stars and galaxies in a universe in which *both* Q and Λ are raised by several orders of magnitude from their present values (see Fig. 2 of ref. [74]). For example, were $\Omega_\Lambda > 100$, one option to explain the existence of galaxies in our universe would be to raise Q .

From the calculations of refs. [74–77], we conclude that, if we make no other assumptions, the pair (Q, Λ) are each about two orders of magnitude smaller than their most likely values, based only on the existence of stars and galaxies. This is non-trivial, since they are many orders of magnitude away from their natural values. But it still leaves a great deal to be explained.

Let us now turn to Weinberg's second argument, in which he employs the PM. I argued above that the PM provides an unreliable basis for deductions, because the results obtained depend strongly on which ensemble is considered to be typical. It is easy to see that Weinberg's second argument supports this conclusion. Were this argument reliable, it would be robust under reasonable changes of the ensemble considered. But, as shown by Graesser and colleagues [77] and earlier authors [63, 64], if the ensemble is taken to be universes in which Λ varies but all other constants are held fixed, then an application of the PM leads to the conclusion that the probability of Λ being as small as observed is around 10%. But if we consider an ensemble in which Q as well as Λ varies, the probability comes down to order 10^{-4} , with the precise estimate depending on various assumptions made (see Table 1 of ref. [77]).

We draw two conclusions from this. First, the PM is unreliable because the conclusions drawn from it are ambiguous in that they depend strongly on the ensemble considered. Second, if taken seriously, it nevertheless leads to the conclusion that the probability of the observed value of Λ is of order 10^{-4} . This is because, in all modern cosmological theories, Q depends on the parameters of the inflation potential, such as its mass and self-coupling. In any fundamental model of particle physics in which parameters vary, these would certainly be among the parameters expected to do so.

Thus, Weinberg's two arguments illustrate the conclusions we reached earlier. The AP itself, in the form of **A** and **B**, makes no predictions. Arguments that it has led to predictions are false; the effective part of the argument is never the existence of life or intelligent observers but only observed facts about our universe. The PM cannot help, because it is easily shown to be unreliable. Any argument that it leads to a correct conclusion can be easily turned into an argument for an incorrect conclusion by reasonable changes in the definition of the ensemble in which we are assumed to be typical.

20.5.7 Aguirre's argument against the Anthropic Principle

We now mention one final argument against the AP, given by Aguirre [78]. He points out that intelligent life would be possible in universes with parameters very different from our own. He gives the particular example of a cold big bang model. This is a class of models which disagree with observations but still have galaxies, carbon and long-lived stars. This is sufficient, because it follows that any argument that incorporates a version of the AP would have to explain why we do not live in a cold big bang universe.

Given that cold big bang universes share the property of our universe of having abundant formation of galaxies and stars, none of the versions of the AP can do this. Thus, either we leave unexplained why we do not live in a cold big bang universe, or we have to find an explanation other than the AP for the parameters of our universe.

20.6 Cosmological Natural Selection

I believe that I have demonstrated conclusively that the version of the AP described by **A** and **B** is never going to give falsifiable predictions for the parameters of physics and cosmology. For the few times an argument called ‘anthropic’ has led to a successful prediction, as in the case of Hoyle’s argument and Weinberg’s first argument, examination shows that it rests entirely on a straightforward deduction from an observed fact about our universe.

Thus, if we are to understand the choices of parameters in the context of a falsifiable theory, we need an alternative approach. One alternative to deriving predictions from a multiverse theory is patterned on the successful model of natural selection in biology. This was also originally motivated by asking the question of how science can explain improbable complexity. To my knowledge, only in biology do we successfully explain why some parameters – in this case the genes of all the species in the biosphere – come to be set to very improbable values, with the consequence that the system is vastly more complex and stable than it would be for random values. The intention is then not to indulge in some mysticism about ‘living universes’, but merely to borrow a successful methodology from the only area of science that has successfully solved a problem similar to the one we face.¹⁵

The methodology of natural selection, applied to multiverse theories, is described by three hypotheses.

- (i) A physical process produces a multiverse with long chains of descendants.
- (ii) For the space $\mathcal{P}$ of dimensionless parameters of the Standard Models of physics, there is a fitness function $F(p)$ on $\mathcal{P}$ which is equal to the average number of descendants of a universe with parameters p .
- (iii) The dimensionless parameters p_{new} of each new universe differ, on average, by *small* random amounts from those of its immediate ancestor

¹⁵ Other approaches to cosmology which employ phenomena analogous to biological evolution have been proposed, for example, by Davies [79], Gribbin [80], Kauffman [81] and Nambu [82]. We note that Linde sometimes employs the term ‘Darwinian’ to describe eternal inflation [83–89]. However, because each universe in eternal inflation has the same ancestor, there is no inheritance and no modification of parameters analogous to the case of biology.

(i.e. small compared with the change that would be required to change $F(p)$ significantly).

Their conjunction leads to a predictive theory, because – using standard arguments from population biology – after many iterations from a large set of random starts, the population of universes, given by a distribution $\rho(p)$, is peaked around local extrema of $F(p)$. With more detailed assumptions, more can be deduced, but this is sufficient to lead to observational tests of these hypotheses. This implies the following prediction.

($\mathcal{S}$) If p is changed from its present value in any direction in $\mathcal{P}$, the first significant changes in $F(p)$ encountered must be to decrease $F(p)$.

The point is that the process defined by the three hypotheses drives the probability distribution $\rho(p)$ to the local maxima of the fitness function and keeps it there. This is much more predictive than the AP, because the resulting probability distribution would then be much more structured and very far from random. If, in addition, the physics that determines the fitness function is well understood, detailed tests of the general prediction $\mathcal{S}$ become possible, as we will now see.

20.6.1 *Predictions of Cosmological Natural Selection*

It is important to emphasize that the process of natural selection is very different from a random sprinkling of universes in the parameter space $\mathcal{P}$, which would produce only a uniform distribution. To achieve a distribution peaked around the local maxima of a fitness function requires two conditions. The change in each generation must be small, so that the distribution can ‘climb the hills’ in $F(p)$ rather than jump around randomly, and so that it can stay in the small volumes of $\mathcal{P}$ where $F(p)$ is large and not diffuse away. It requires many steps to reach local maxima from random starts, which implies that long chains of descendants are needed.

As a result, of the two mechanisms for universe production studied so far, only black hole bouncing fits the conditions necessary for natural selection. This is also fortunate, because the physics that goes into the fitness function is well understood in this case, at least in the neighbourhood of the parameters of our universe. The physical processes that strongly influence the number of black holes produced are nucleosynthesis, galaxy formation, star formation, stellar dynamics, supernova explosions and the formation and stability of neutron stars. All of these processes, except perhaps galaxy formation, are understood in some detail, and in several of them our theories

make precise predictions which have been tested. We are then on reasonably firm ground asking what happens to each of these processes when we make small changes in the parameters. Thus, for the rest of this chapter, CNS will be taken to mean the process of reproduction of universes through black hole bounces, supplemented by the above hypotheses.

The hypothesis that the parameters p change by small random amounts should be ultimately grounded in fundamental physics. We note that this is compatible with string theory, in the sense that a great many string vacua likely populate the space of low-energy parameters. It is plausible that when a region of the universe is squeezed to the Planck density and heated to the Planck temperature, phase transitions may occur, leading to jumps from one string vacua to another. But so far there have been no detailed studies of these processes which would have checked the hypothesis that the change in each generation is small. One study of a bouncing cosmology in quantum gravity also lends support to the hypothesis that the parameters change in each bounce [90].

20.6.2 *Successes of the theory*

Details of the arguments for CNS, as well as references to the astrophysical literature on which the arguments are founded, can be found in [13–17]. Here I will only summarize the conclusions. The crucial conditions necessary for forming many black holes as the result of massive star formation are as follows.

- There should be a few light stable nuclei, at least up to helium, so that gravitational collapse leads to long-lived stable stars.
- Carbon and oxygen nuclei should be stable, so that giant molecular clouds form and cool efficiently, giving rise to the efficient formation of stars massive enough to give rise to black holes.
- The number of massive stars is increased by feedback processes, whereby massive star formation catalyzes more massive star formation. This is called ‘self-propagated star formation’, and there is good evidence that it makes a significant contribution to the number of massive stars produced. This requires a separation between the timescale required for star formation and the lifetime of massive stars, which implies – among other things – that nucleosynthesis should not proceed so far that the universe is dominated by long-lived hydrogen-burning stars.
- Feedback processes involved in star formation also require that supernovae should eject enough energy and material to catalyze the formation

of massive stars, but not so much that there are not many supernova remnants over the upper mass limit for stable neutron stars.

- The parameters governing nuclear physics should be tuned, as much as possible consistent with the foregoing, so that the upper mass limit for neutron stars is as low as possible.

The study of the first four conditions leads to the conclusion that the number of black holes produced in galaxies will be decreased by almost any change in low-energy parameters: a reversal of the sign of $\Delta m = m_n - m_p$ will result in a universe dominated by a gas of neutrons; a small increase in Δm compared to m_n will destabilize helium and carbon; an increase in m_e of order m_e will destabilize helium and carbon; an increase in m_ν of order m_e will destabilize helium and carbon; a small increase in α will destabilize all nuclei; a small decrease in α_s , the strong coupling constant, will destabilize all nuclei; an increase or decrease in G_F , the Fermi constant, of order unity will decrease the energy output of supernovae, and one sign will lead to a universe dominated by helium. Thus, the CNS hypothesis explains the values of all the parameters that determine low-energy physics and chemistry: the masses of the proton, neutron, electron and neutrino and the strengths of the strong, weak and electromagnetic interactions.

However, explanation is different from prediction. These cannot be considered independent predictions of the theory, because the existence of carbon and oxygen, plus long-lived stars, are also conditions of our own existence. Hence selection effects prevent us from claiming these as unique predictions of CNS. If the theory is to make falsifiable tests, it must involve changes of parameters that do not affect the conditions necessary for our own existence. There are such tests, and they will be described shortly. Before discussing them, however, we should address several criticisms that have been made.

20.6.3 Previous criticisms

Several arguments have been made that $\mathcal{S}$ is contradicted by present observation [91–93]. These are found to depend either on confusion about the hypothesis itself or on too simple assumptions about star formation. For example, it was argued in ref. [91] that star formation would proceed to more massive stars were the universe to consist only of neutrons, because there would be no nuclear processes to impede direct collapse to black holes. This kind of argument ignores the fact that the formation of stars massive enough to become black holes requires efficient cooling of giant molecular clouds. The cooling processes that appear to be dominant require carbon and oxygen, both for formation of CO, whose vibrational modes are the most

efficient mechanism of cooling, and because dust grains consisting of carbon and ice provide efficient shielding of star-forming regions from starlight. But even processes cooling molecular clouds to 5–20 K are not enough; formation of massive stars appears to require that the cores of the cold clouds are disturbed by shock-waves, which come from ionized regions around other massive stars and supernovae. For these reasons, our universe appears to produce many more black holes than would a universe consisting of just neutrons.¹⁶

Vilenkin (personal communication) has raised an issue concerning the cosmological constant. Were Λ (the vacuum energy) raised from its present value, he notes that galaxy formation would not have taken place at all. One might add that, with even a slight increase, galaxy formation would have been cut off, leading only to small galaxies unable to sustain the process of self-propagated star formation that is apparently necessary for copious formation of massive stars. This counts as a success of the theory.

On the other hand, were Λ smaller than its present value, there might be somewhat increased massive star formation, due to the fact that, at the present time, the large spiral galaxies are continuing to accrete matter through several processes. These include the accretion of intergalactic gas onto the disks of galaxies and the possible flow of gas from large gaseous disks that the visible spiral galaxies may be embedded in. It is difficult to estimate exactly how much the mass of spiral galaxies would be increased by this process, but Vilenkin claims it could be as much as 10–20%.

However, lowering Λ would also increase the number of mergers of spiral galaxies and the number of absorptions of dwarf galaxies by spirals. These mergers and absorptions are believed to convert spiral galaxies to elliptical galaxies by destroying the stellar disk and heating the gas. The result is to cut off the formation of massive stars, leaving much gas unconverted to stars.

There is then a competition between two effects. Raise Λ and galaxies do not form or do not grow large enough to support disks and hence massive star formation. Decrease Λ and the dominant effect may be to cut off massive star formation, due to increased mergers and absorptions converting spiral to elliptical galaxies. One can conjecture that the present value of Λ maximizes the formation of black holes.

It has also been claimed that $\mathcal{S}$ is untestable with present knowledge [93, 94]. In the following, I will show that these claims are also false, by explaining

¹⁶ For details, see the appendix of ref. [17], which addresses the objections published in refs. [91]–[93] and elsewhere.

why a single observation of an astrophysical object that very well might exist – a heavy neutron star – would refute $\mathcal{S}$. After this, I describe two more kinds of observations that could refute $\mathcal{S}$ in the near future. These involve more accurate observations of the spectrum of fluctuations in the cosmic microwave background (CMB) and the initial mass function for star formation in the absence of carbon.

20.6.4 *Why a single heavy pulsar would refute $\mathcal{S}$*

Bethe and Brown [95] have hypothesized that neutron star cores contain a condensate of K^- mesons. Their calculations show that there is a critical value μ_c for the strange quark mass μ such that, for $\mu < \mu_c$, neutron star cores consist of approximately equal numbers of protons and neutrons with the charge balanced by a condensate of K^- mesons. The reason is that in nuclear matter the effective mass of the K^- is renormalized downward by an amount depending on the density ρ . Given a choice of the strange quark mass, let $\rho_0(\mu)$ be the density where the renormalized kaon mass is less than the electron mass. Then μ_c is the value of μ where $\rho_0(\mu)$ becomes less than the density ρ_e at which the electrons react with the protons to form neutrons. In either case, one neutrino per electron is produced, leading to a supernova.

Bethe and Brown and collaborators [95–98] claim that $\mu < \mu_c$ but their calculations involve approximations, such as chiral dynamics, so are insufficiently accurate to exclude $\mu_c > \mu$. However, as μ decreases, the accuracy of the calculations increases as μ^{-2} , so, even if we are not sure that $\mu < \mu_c$, we can be reasonably confident of the existence of a critical value μ_c . We may then reason as follows. If $\mu < \mu_c$, the upper mass limit is low, approximately $1.5M_\odot$. If $\mu > \mu_c$, neutron stars have the conventional equations of state and the upper mass limit is higher, almost certainly above $2M_\odot$ [99]. Therefore, a single observation of a neutron star whose mass was sufficiently high could show $\mu > \mu_c$, refuting Bethe and Brown’s claim. A mass of $2.5M_\odot$ would certainly suffice, although any value higher than $1.5M_\odot$ would be troubling if one believed Bethe and Brown’s upper limit. Furthermore, this would refute $\mathcal{S}$ because a decrease in μ would then lead to a world with a lower upper mass limit for neutron stars, and therefore more black holes. All well measured neutron star masses are currently from binary pulsar data and are below $1.5M_\odot$ [100, 101]; other methods yield less precise estimates [102].

We note that this argument is independent of any issue of selection effects associated with ‘anthropic reasoning’, because the value of the strange quark mass μ may be varied within a large range before it produces a significant

effect on chemistry. Sceptics might reply that, were $\mathcal{S}$ so refuted, it could be modified to a new unrefuted $\mathcal{S}'$ by the additional hypothesis that μ is not an independent parameter and cannot be varied without also, say, changing the proton–neutron mass difference, leading to large effects in star formation. Of course, most theories can be saved by the proliferation of *ad hoc* hypotheses, but science tends to reject hypotheses that require special fixes. There are occasions where such a fix is warranted. The present case would only be among them if there were a preferred fundamental theory, which had strong independent experimental support, in which μ was not an independent parameter but could not be changed without altering the values of parameters that strongly affect star formation and evolution.

20.6.5 How observations of the CMB could refute $\mathcal{S}$

It might be observed that there would have been many more primordial black holes (PBHs) if the spectrum of primordial fluctuations, $f(n)$, were tilted to increase their amplitude on small scales [103]. This does not refute $\mathcal{S}$ directly unless the inflationary model has a parameter that can be varied to achieve this tilt. The Standard Model does not, but it is reasonable to examine whether some plausible extension of it, $\mathcal{E}$, might do so. One plausible extension is to add a field that could serve as the inflaton. The spectrum of primordial fluctuations may then be predicted as a function of the parameters of $\mathcal{E}$. Thus $\mathcal{S}$ is refuted if (a) some model $\mathcal{E}$ of inflation is observationally confirmed and (b) that particular model has some parameter, p_{inf} , that can be modified to *increase the total number of PBHs produced*. Given the accuracy expected for observations of the CMB from the WMAP and PLANCK satellites, there is a realistic possibility that these will distinguish between different hypotheses $\mathcal{E}$ and measure the values of their parameters.

In the standard ‘new’ inflationary scenario [34], there is no parameter that fulfils the function required of p_{inf} . There is the inflaton coupling, λ , and it is true that the amplitude of $f(n)$ is proportional to λ , so that the number of PBHs can be increased by increasing this. However, the size of the region that inflates, R , scales as $e^{\lambda^{-1/2}}$. This means that λ should be at the lower limit of the range of values for which galaxy formation occurs. An exponentially larger universe, which produces black holes only through supernova remnants, still has vastly more black holes than an exponentially smaller universe with many primordial black holes. In fact, if the observations confirm the new inflationary scenario, $\mathcal{S}$ is refuted if λ is not tuned to the value that maximizes the total production of black holes in the inflated

region [13]. Because of the exponential decrease in R with increasing λ , this is likely to be close to the *smallest* value that leads to appreciable black hole production. This should correspond to the smallest λ that allows prolific formation of galaxies [13].

This seems consistent with the actual situation, in which there appears to have been little PBH production. Therefore, given that $Q \equiv \delta\rho/\rho \approx 10^{-5}$, the primary mode of production of black holes seems to be through massive star production in galaxies that do not form until rather late. However, there are non-standard models of inflation that have parameters p_{inf} that can be varied in a manner that tilts $f(n)$ so that more PBHs are created without decreasing R [104–109]. If future CMB observations show that standard new inflation is ruled out, so that only models with such a parameter p_{inf} are allowed, then $\mathcal{S}$ will be refuted. This is a weaker argument than the first one, but – given the scope for increased accuracy of the CMB measurements – such a refutation is plausible.

20.6.6 How early star formation could refute $\mathcal{S}$

As shown in refs. [6, 13, 94], there are several directions in $\mathcal{P}$ which lead to universes that contain no stable nuclear bound states. It is argued in refs. [13, 17] that this leads to a strong decrease in $F(p)$, because the gravitational collapse of objects more massive than the upper mass limit of neutron stars seems to depend on the cooling mechanisms in giant molecular clouds, which are dominated by radiation from CO. In a universe without nuclear bound states, the upper mass limit for stable collapsed objects is unlikely to decrease dramatically (as the dominant factor ensuring stability is Fermi statistics), while collapsed objects larger than the upper mass limit are likely to be less common without CO cooling.

In the absence of bound states, the main cooling mechanism involves molecular hydrogen [110], but there are two reasons to suppose this would not lead to plentiful collapse of massive objects in a world with nuclear bound states. The first is that there would be no dust grains, and these appear to be the primary catalysts for the binding of molecular hydrogen. The second is that molecular hydrogen is, anyway, a less efficient coolant than CO [110]. Given present uncertainties in star formation processes, this is a weaker argument than the first. However, since these uncertainties are unlikely to be reduced in the near future, let us ask whether this argument could be refuted by any possible observations.

In the present universe the collapse of massive objects is dominated by processes that involve nuclear bound states, but we have a laboratory for

the collapse of objects in the absence of nuclear bound states – our universe before enrichment with metals. Indeed, we know that massive objects must have collapsed then, otherwise carbon, oxygen and other elements would never have been produced. But, given that CO acts as a catalyst for the formation of heavy elements and that the dust formed from heavy elements produced in stars is a catalyst for molecular binding, there is an instability whereby any chance formation of massive objects leads in a few million years to both an enrichment of the surrounding medium and the production of significant quantities of dust. These greatly increase the probability of forming additional massive objects, so the initial rate of formation of heavy objects in the absence of enrichment does not have to be very high to explain how our universe first became enriched.

This shows that the collapse of some heavy objects before enrichment does not refute the argument that the number of black holes produced in a universe without nuclear bound states would be much less than at present. But nor does it establish the argument. It is still consistent with present knowledge that the production of massive objects in the absence of heavy elements proceeds efficiently under the right conditions, so that there may have been a great deal of early star formation uncatalyzed by any process involving heavy elements. This could lead to a refutation of $\mathcal{S}$ because, in a world without nuclear bound states, many more massive collapsed objects would become black holes than do in our universe, where the collapse is delayed by stellar nucleosynthesis.

The question is then whether a combination of observation and theory could disentangle the strong catalytic effects of heavy elements, leading to a strong positive feedback in massive star formation, from the initial rate of massive star formation without heavy elements. Although models of star formation, with and without heavy elements are not sufficiently developed to distinguish the two contributions at early times, it is likely that this will become possible as our star formation models improve. If so, future observations may yield enough information about early star formation to distinguish the two effects. If the conclusion is that the number of black holes formed is greater in a world without nuclear bound states than in our own, then $\mathcal{S}$ would be refuted.

20.7 Conclusions

This chapter was written with the hope of contributing to a debate about the possible role of the AP in physics and cosmology. Having carefully considered the arguments and engaged several proponents in conversation

and correspondence, it seems to me incontrovertible not only that the AP is unscientific, but also that its role is negative. To the extent that it is espoused to justify continued interest in unfalsifiable theories, it may play a destructive role in the progress of science. The main points of my argument are as follows.

- No theory can be a candidate for a physical theory that does not make falsifiable predictions. To violate this maxim is to risk the development of a situation in which the scientific community splits into groups divided by different unverifiable faiths, because there is no possibility of killing popular theories by rational argument from shared evidence.
- The version of the AP described by **A** and **B** cannot lead to falsifiable theories.
- Claimed successful predictions of anthropic reasoning involve either uncontroversial use of selection effects within one universe, as in the argument of Dicke, or simple deductions from observed facts, with life or ensembles of universes playing no role in the prediction, as in the arguments of Hoyle and Weinberg. There are no successful anthropic predictions that do not fall into these two classes. Hence all claims for the success of the AP are false.
- The Principle of Mediocrity is ambiguous, because a reasonable change in the definition of the ensemble in which we or our civilization are taken to be typical can often turn an argument for a correct conclusion into an argument for an incorrect one. In specific applications, it is often unreliable. When the claims made can be tested, as in the doomsday argument, it often leads to false conclusions.
- Eternal inflation cannot lead to an explanation of the low-energy parameters of the Standard Model and thus to a resolution of why these parameters allow stars and organic chemistry, because these parameters play no role in the mechanism that generates the probability distribution for universes created by eternal inflation.
- It is possible to derive falsifiable predictions from a multiverse theory if the following conditions are satisfied: (1) the ensemble of universes generated differs strongly from a random ensemble, constructed from an unbiased measure; (2) almost all members of the ensemble have a property $\mathcal{W}$ that is not a consequence of either the known laws of physics or a requirement for the existence of life; (3) it must be possible to establish whether $\mathcal{W}$ is true or not in our universe by a practical experiment.
- There is at least one example of a falsifiable theory satisfying these conditions, which is CNS. Among the properties $\mathcal{W}$ that make the theory

falsifiable is that the upper mass limit of neutron stars is less than $1.6M_{\odot}$. This and other predictions of CNS have yet to be falsified, but they could be by observations in progress.

It must then be considered unacceptable for any fundamental theory of physics to rely on the AP in order to make contact with observations. When such claims are made, as they have been recently for string theory [31–33], this can only be considered as a sign that the theory is in deep trouble and at great risk of venturing outside the bounds of science.

There are, of course, alternatives. String theory might be shown to imply the conditions necessary for CNS, in which case it would yield falsifiable predictions. Or another mechanism for the selection of parameters might turn out to lead to falsifiable predictions. What is clear is that some falsifiable version of the theory must be found. Otherwise the theory cannot be considered scientific, because there will be no way to establish its truth or falsity by a means which allows consensus to be established by rational argument from shared evidence.

Acknowledgements

I am grateful to numerous people for conversation and correspondence on these topics, including Anthony Aguirre, Stephon Alexander, Tom Banks, John Barrow, Michael Dine, George Ellis, Ted Jacobson, Joao Magueijo, Fotini Markopoulou, John Moffat, Slava Mukhanov, Holger Nielsen, Joe Polchinski, Martin Rees, Sherrie Roush, Alex Vilenkin, Peter Woit, and colleagues at Perimeter Institute. I am also grateful to Michael Douglas, Jaume Garriga, Leonard Susskind, Alex Vilenkin and Steven Weinberg for helpful clarifications and references. This research was supported partly by the Jesse Phillips Foundation. Finally, I am grateful to the Templeton Foundation and the organizers of the 2001 Cambridge Conference for including anthro-sceptics like myself in the debate, in the true spirit of science.

References

- [1] K. Popper. *Conjectures and Refutations* (London: Routledge and Keagan Paul, 1963), pp. 33–39.
- [2] K. Popper. In *Readings in the Philosophy of Science*, ed. T. Schick (Mountain View, CA: Mayfield Publishing Company, 2000), pp. 9–13.
- [3] K. Popper. *The Open Society and its Enemies* (Princeton, NJ: Princeton University Press, 1971).
- [4] K. Popper. *The Logic of Scientific Discovery* (London: Routledge, 1992).
- [5] L. Smolin. *The Trouble with Physics* (Boston, MA: Houghton Mifflin, 2006).

- [6] B. J. Carr and M. J. Rees. The anthropic principle and the structure of the physical world. *Nature* **278** (1979), 605.
- [7] B. Carter. The significance of numerical coincidences in nature. Cambridge University preprint (1967).
- [8] B. Carter. Number coincidences and the anthropic principle in cosmology. In *Confrontation of Cosmological Theories with Observational Data, IAU Symposium No. 63*, ed. M. Longair (Dordrecht: Reidel, 1974), p. 291.
- [9] J. D. Barrow and F. J. Tipler *The Anthropic Cosmological Principle* (Oxford: Oxford University Press, 1986).
- [10] S. Roush. Copernicus, Kant, and the anthropic cosmological principles. *Stud. Hist. Phil. Mod. Phys.* **34** (2003), 5–35.
- [11] S. Roush. Anthropic principle. In *The Philosophy of Science: An Encyclopedia*, eds. J. Pfeifer and S. Sarkar (London: Routledge, 2003).
- [12] A. Feoli and S. Rampone. Is the strong anthropic principle too weak? *Nuovo Cim.* **B 114** (1999), 281.
- [13] L. Smolin. Did the universe evolve? *Class. Quant. Grav.* **9** (1992), 173.
- [14] L. Smolin. On the fate of black hole singularities and the parameters of the standard model. [gr-qc/9404011].
- [15] L. Smolin. Cosmology as a problem in critical phenomena. In *Proceedings of the Guanajuato Conference on Complex Systems and Binary Networks*, eds. R. Lopez-Pena, R. Capovilla, R. Garcia-Pelayo, H. Waalebroeck and F. Zertuche (Berlin: Springer, 1995) [gr-qc/9505022].
- [16] L. Smolin. Experimental signatures of quantum gravity. In *Proceedings of the Fourth Drexel Conference on Quantum Nonintegrability*, eds. B. L. Hu and D. H. Feng (Boston: International Publishers, 1996) [gr-qc/9503027].
- [17] L. Smolin. *The Life of the Cosmos* (New York: Oxford University Press, 1997).
- [18] P. Binetruy, G. L. Kane, B. D. Nelson, L-T. Wang and T. T. Wang. Relating incomplete data and incomplete theory. *Phys. Rev.* **D 70** (2004), 095006 [hep-ph/0312248].
- [19] F. Markopoulou. Towards gravity from the quantum (2006) [hep-th/0604120].
- [20] D. W. Kribs and F. Markopoulou. Geometry from quantum particles (2005) [gr-qc/0510052].
- [21] S. O. Bilson-Thompson, F. Markopoulou and L. Smolin. Quantum gravity and the standard model (2006) [hep-th/0603022].
- [22] S.O. Bilson-Thompson. A topological model of composite preons. (2005) [hep-ph/0503213].
- [23] T. Thiemann. The LQG – string-loop quantum gravity quantization of string theory I. Flat target space. *Class. Quant. Grav.* **23** (2006), 1923–1970 [hep-th/0401172].
- [24] L. Smolin. How far are we from the quantum theory of gravity? (2003) [hep-th/0303185].
- [25] S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi. de Sitter vacua in string theory. *Phys. Rev.* **D 68** (2003), 046005 [hep-th/0301240].
- [26] S. B. Giddings, S. Kachru and J. Polchinski. Hierarchies from fluxes in string compactifications. *Phys. Rev.* **D 66** (2002), 106006 [hep-th/0105097].
- [27] R. Bousso and J. Polchinski. Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. *JHEP*, **0006** (2000), 006 [hep-th/0004134].
- [28] L. Susskind. This volume (2007) [hep-th/0302219].

- [29] M. Douglas. The statistics of string/M theory vacua. *JHEP*, **0305** (2003), 046 [hep-th/0303194].
- [30] M. Douglas. Statistical analysis of the supersymmetry breaking scale (2004) [hep-th/0405279].
- [31] A. H. Guth. The inflationary universe: A possible solution to the horizon and flatness problems. *Phys. Rev. D* **23** (1981), 347.
- [32] A. D. Linde. A new inflationary universe scenario: A possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems. *Phys. Lett. B* **108** (1982), 389.
- [33] A. Albrecht and P. J. Steinhardt. Cosmology for grand unified theories with radiatively induced symmetry breaking. *Phys. Rev. Lett.* **48** (1982), 1220.
- [34] A. D. Linde. *Particle Physics and Inflationary Cosmology* (Chur, Switzerland: Harwood Academic, 1990).
- [35] P. J. Steinhardt and N. Turok. A cyclic model of the universe. *Science*, **296** (2002), 1436.
- [36] Cosmic evolution in a cyclic universe. *Phys. Rev. D* **65** (2002), 126003 [hep-th/0111098].
- [37] J. W. Moffat. Superluminary universe: A possible solution to the initial value problem in cosmology. *Int. J. Mod. Phys. D* **2** (1993), 351 [gr-qc/9211020].
- [38] A. Albrecht and J. Magueijo. A time varying speed of light as a solution to cosmological puzzles. *Phys. Rev. D* **59** (1999), 043516 [astro-ph/9811018].
- [39] J. D. Barrow. Cosmologies with varying light speed. *Phys. Rev. D* **59** (1999), 043515.
- [40] J. Magueijo. New varying speed of light theories. *Rep. Prog. Phys.* **66** (2003), 2025 [astro-ph/0305457].
- [41] A. Vilenkin. The birth of inflationary universes. *Phys. Rev. D* **27** (1983), 2848.
- [42] A. Linde. The inflationary universe. *Rep. Prog. Phys.* **47** (1984), 925.
- [43] A. Linde, D. Linde and A. Mezhlumian. From the big bang theory to the theory of a stationary universe. *Phys. Rev. D* **49** (1994), 1783 [gr-qc/9306035].
- [44] J. Garcia-Bellido and A. Linde. Stationarity of inflation and predictions of quantum cosmology. *Phys. Rev. D* **51** (1995), 429 [hep-th/9408023].
- [45] J. Garriga and A. Vilenkin. A prescription for probabilities in eternal inflation. *Phys. Rev. D* **64** (2001), 023507 [gr-qc/0102090].
- [46] J. A. Wheeler. Beyond the end of time. In *Black Holes, Gravitational Waves and Cosmology: An Introduction to Current Research*, eds. M. Rees, R. Ruffini and J.A. Wheeler (New York: Gordon and Breach).
- [47] C. Misner, K. Thorne and J. A. Wheeler. *Gravitation* (San Francisco: Freeman, 1974).
- [48] V. P. Frolov, M. A. Markov and M. A. Mukhanov. Through a black hole into a new universe? *Phys. Lett. B* **216** (1989), 272.
- [49] A. Lawrence and E. Martinec. String field theory in curved space-time and the resolution of spacelike singularities. *Class. Quant. Grav.* **13** (1996), 63 [hep-th/9509149].
- [50] E. Martinec. Spacelike singularities in string theory. *Class. Quant. Grav.* **12** (1995), 941 [hep-th/9412074].
- [51] M. Bojowald. Isotropic loop quantum cosmology. *Class. Quant. Grav.* **19** (2002), 2717 [gr-qc/0202077].
- [52] M. Bojowald. Inflation from quantum geometry. *Phys. Rev. Lett.* **89** (2002), 261301 [gr-qc/0206054].

- [53] M. Bojowald. The semi-classical limit of loop quantum cosmology. *Class. Quant. Grav.* **18** (2001), L109 [gr-qc/0105113].
- [54] M. Bojowald. Dynamical initial conditions in quantum cosmology. *Phys. Rev. Lett.* **87** (2001), 121301 [gr-qc/0104072].
- [55] S. Tsujikawa, P. Singh and R. Maartens. Loop quantum gravity effects on inflation and the CMB. *Class. Quant. Grav.* **21** (2003), 5767 [astro-ph/0311015].
- [56] V. Husain and O. Winkler. Quantum resolution of black hole singularities. *Class. Quant. Grav.* **22** (2005), L127 [gr-qc/0410125].
- [57] L. Modesto. Disappearance of black hole singularity in quantum gravity. *Phys. Rev. D* **70** (2004), 124009 [gr-qc/0407097].
- [58] A. Ashtekar and M. Bojowald. Quantum geometry and the Schwarzschild singularity. *Class. Quant. Grav.* **23** (2006), 391 [gr-qc/0509075].
- [59] R. H. Dicke. Principle of equivalence and weak interactions. *Rev. Mod. Phys.* **29** (1957), 355.
- [60] P. A. M Dirac. The cosmological constants. *Nature*, **139** (1937), 323.
- [61] F. Hoyle. On the fragmentaion of gas clouds into galaxies and stars. *Astrophys. J.* **118** (1953), 513.
- [62] A. Vilenkin. Predictions from quantum cosmology. *Phys. Rev. Lett.* **74** (1995), 846 [gr-qc/9406010].
- [63] J. Garriga and A. Vilenkin. Testable anthropic predictions for dark energy. *Phys. Rev. D* **67** (2003), 043503 [astro-ph/0210358].
- [64] J. Garriga, M. Livio and A. Vilenkin. The cosmological constant and the time of its dominance. *Phys. Rev. D* **61** (2000), 023503 [astro-ph/9906210].
- [65] S. Weinberg. Anthropic bound on the cosmological constant. *Phys. Rev. Lett.* **59** (1987), 2067.
- [66] H. Martel, P. Shapiro and S. Weinberg. Likely values of the cosmological constant. *Astrophys. J.* **492** (1998), 29 [astro-ph/9701099].
- [67] S. Weinberg. A priori probability distribution of the cosmological constant. *Phys. Rev. D* **61** (2000), 103505 [astro-ph/0002387].
- [68] S. Weinberg. The cosmological constant problems. In *Sources and Detection of Dark Matter and Dark Energy in the Universe*, ed. D. Cline (New York: Springer-Verlag, 2000) [astro-ph/0005265].
- [69] H. Nielsen. Random dynamics and relations between the number of fermion generations and the fine structure constants. *Act. Phys. Polon. B* **20** (1989), 427.
- [70] J. R. Gott III. Implications of the Copernican principle for our future prospects. *Nature*, **363** (1993), 315.
- [71] J. Leslie. *The End of the World. The Ethics and Science of Human Extinction* (London: Routledge, 1996).
- [72] F. Markopoulou. The internal description of a causal set: What the universe looks like from the inside. *Commun. Math. Phys.* **211** (2000), 559 [gr-qc/9811053].
- [73] M. Ahmed, S. Dodelson, P. B. Greene and R. Sorkin. Ever-present lambda. *Phys. Rev. D* **69** (2004), 103523 [astro-ph/0209274].
- [74] M. J. Rees. Anthropic reasoning. Clues to a fundamental theory. *Complexity*, **3** (1997), 17.
- [75] M. J. Rees. Numerical coincidences and ‘tuning’ in cosmology. In *Fred Hoyle’s Universe*, eds. C. Wickramasinghe, G. Burbidge and J. V. Narlikar (Dordrecht: Kluwer, 2003), p. 87.

- [76] M. Tegmark and M. J. Rees. Why is the CMB fluctuation level 10^{-5} ? *Astrophys. J.* **499** (1998), 526 [astro-ph/9709058].
- [77] M. L. Graesser, S. D. H. Hsu, A. Jenkins and M. B. Wise. Anthropic distribution for cosmological constant and primordial density perturbations. *Phys. Lett. B* **600** (2004), 15 [hep-th/0407174].
- [78] A. Aguirre. The cold big-bang cosmology as a counter-example to several anthropic arguments. *Phys. Rev. D* **64** (2001), 083508 [astro-ph/0106143].
- [79] P. Davies. *The Mind of God* (New York: Simon and Schuster, 1991).
- [80] J. Gribbin. *In the Beginning: After COBE and Before the Big Bang* (New York: Little Brown, 1993).
- [81] S. Kauffman. *Investigations into Autonomous Agents* (Oxford: Oxford University Press, 2002).
- [82] Y. Nambu. Distribution of particle physics. *Prog. Theor. Phys. Suppl.* **85** (1985), 104.
- [83] A. Linde. Particle physics and inflationary cosmology. *Phys. Today*, **40** (1987), 61.
- [84] A. Linde. *Particle Physics and Inflationary Cosmology* (Chur, Switzerland: Harwood, 1990).
- [85] A. Linde. Universe multiplication and the cosmological constant problem. *Phys. Lett. B* **200** (1988), 272.
- [86] A. Linde. Life after inflation and the cosmological constant problem. *Phys. Lett. B* **227** (1989), 352.
- [87] A. Linde. Extended chaotic inflation and spatial variations of the gravitational constant. *Phys. Lett. B* **238** (1990), 1680.
- [88] J. Garcia-Bellido, A. Linde and D. Linde. Fluctuations of the gravitational constant in the inflationary Brans-Dicke cosmology. *Phys. Rev. D* **50** (1994), 730 [astro-ph/9312039].
- [89] J. Garcia-Bellido and A. Linde. Stationary solutions in Brans-Dicke stochastic inflationary cosmology. *Phys. Rev. D* **52** (1995), 6780 [gr-qc/9504022].
- [90] R. Gambini and J. Pullin. Discrete quantum gravity: A mechanism for selecting the value of fundamental constants. *Int. J. Mod. Phys. D* **12** (2003), 1775 [gr-qc/0306095].
- [91] T. Rothman and G. F. R. Ellis. Smolin's natural selection hypothesis. *Quart. J. Roy. Astron. Soc.* **34** (1993), 201.
- [92] E. R. Harrison. The natural selection of universes containing intelligent life. *Quart. J. Roy. Astron. Soc.* **36** (1995), 193.
- [93] J. Silk. *Science*, **227** (1997), 644.
- [94] M. Rees. In *Before the Beginning* (Reading, MA: Addison Wesley, 1997).
- [95] G. E. Brown and H. A. Bethe. A scenario for a large number of low-mass black holes in the Galaxy. *Astrophys. J.* **423** (1994), 659.
- [96] G. E. Brown and J. C. Weingartner. Accretion onto and radiation from the compact object formed in SN 1987A. *Astrophys. J.* **436** (1994), 843.
- [97] G. E. Brown. Kaon condensation in dense matter. *Nucl. Phys. A* **574** (1994), 217.
- [98] H. A. Bethe and G. E. Brown. Observational constraints on the maximum neutron star mass. *Astrophys. J. Lett.* **445** (1995), L129.
- [99] G. B. Cook, S. L. Shapiro and S.A. Teukolsky. Rapidly rotating neutron stars in general relativity. Realistic equations of state. *Astrophys. J.* **424** (1994), 823.

- [100] S. E. Thorsett, Z. Arzoumanian, M. M. McKinnon and J. H. Taylor. The masses of two binary neutron star systems. *Astrophys. J. Lett.* **405** (1993), L29.
- [101] D. J. Nice, R. W. Sayer and J. H. Taylor. PSR J1518+4904: A mildly relativistic binary pulsar system. *Astrophys. J.* **466** (1996), L87.
- [102] J. Casares, P. Charles and E. Kuulkers. The mass of the neutron star in Cyg X-2 (V1341 Cyg). *Astrophys. J. Lett.* **493** (1997), L39.
- [103] B. J. Carr, J. H. Gilbert and J. E. Lidsey. Black hole relics from inflation: Limits on blue perturbation spectra. *Phys. Rev.* **D 50** (1994), 4853.
- [104] M. Bucher, A. S. Goldhaber and N. Turok. An open universe from inflation. *Phys. Rev.* **D 52** (1995), 3314–3337 [hep-ph/9411206, PUPT-94-1507].
- [105] M. Bucher and N. Turok. Open inflation with arbitrary false vacuum mass. *Phys. Rev.* **D 52** (1995), 5538–5548 [hep-ph 9503393, PUPT-95-1518].
- [106] J. R. Gott. Creation of open universes from de Sitter space. *Nature*, **295** (1982), 304.
- [107] J. Garcia-Bellido and A. Linde. Tilted hybrid inflation. *Phys. Lett.* **B 398** (1997), 18 [astro-ph/9612141].
- [108] J. Garcia-Bellido and A. Linde. Open hybrid inflation. *Phys. Rev.* **D 55** (1997), 7480–7488 [astro-ph/9701173].
- [109] D. H. Lyth and A. Riotto. Particle physics models of inflation and the cosmological density perturbation. *Phys. Rep.* **314** (1999), 1 [hep-ph/9807278].
- [110] M. Tegmark, J. Silk, M. Rees, A. Blanchard, T. Abel and F. Palla. How small were the first cosmological objects? *Astrophys. J.* **474** (1997), 1 [astro-ph/9603007].

21

Making predictions in a multiverse: conundrums, dangers, coincidences

Anthony Aguirre

Department of Physics, University of California, Santa Cruz

21.1 Introduction

The Standard Models of particle physics and cosmology are both rife with numerical parameters that must have values fixed by hand to explain the observed world. The world would be a radically different place if some of these constants took a different value. In particular, it has been argued that if any one of six (or perhaps a few more) numbers did not have rather particular values, then life as we know it would not be possible [1]; atoms would not exist, or no gravitationally bound structures would form in the Universe, or some other calamity would occur that would appear to make the alternative universe a very dull and lifeless place. How, then, did we get so lucky as to be here?

This question is an interesting one because all of the possible answers to it that I have encountered or devised entail very interesting conclusions. An essentially exhaustive list of such answers follows.

- (i) We just got very lucky. All of the numbers could have been very different, in which case the Universe would have been barren, but they just happened by pure chance to take values in the tiny part of parameter space that would allow life. We owe our existence to one very, very, very lucky roll of the dice.
- (ii) We were not particularly lucky. Almost any set of parameters would have been fine, because life would find a way to arise in nearly any type of universe. This is quite interesting because it implies (at least theoretically) the existence of life-forms radically different from our own, for example existing in universes with no atoms or bound structures, or overrun with black holes, etc.
- (iii) The Universe was specifically designed for life. The choice of constants only happened once, but their values were determined in some way by

the need for us to arise. This might involve divine agency or some radical form of Wheeler’s ‘self-creating universe’ or super-advanced beings that travel back in time to set the constants at the beginning of the Universe, etc. However one feels about this possibility, one must admit that it would be interesting if true.

- (iv) We did not have to get lucky, because there are many universes with different sets of constants, i.e. the dice were rolled many, many times. We are necessarily in one of the universes that allows life, just as we necessarily reside on a planet that supports life, even when most others may not. This is interesting because it means that there are other very different universes coexisting with ours in a ‘multiverse’.

These four answers – luck, *élan vital*, design and multiverse – will appeal at different levels to different people. But I think it is hard to argue that the multiverse is necessarily less reasonable than the alternatives. Moreover, as discussed at length elsewhere in this volume, there are independent reasons to believe – on the basis of inflation, quantum cosmology and string/M-theory – that there might naturally be many regions outside the observable one, governed by different sets of low-energy physics. I am not aware of any independent scientific argument for the other three possible explanations.

Whether they are contemplated as an answer to the ‘why are we lucky’ question, or because they are forced upon us from other considerations, multiverses come at a high price. Even if we have in hand a physical theory and cosmological model that lead to a multiverse, how do we test it? If there are many sets of constants, which ones do we compare to those we observe? In Section 21.2, I will outline what I think a sound prediction in a multiverse would look like. As will become clear, this requires many ingredients and there are serious difficulties in generating some of these ingredients, even with a full theory in hand. For this reason, many short-cuts have been devised to try to make predictions more easily. In Section 21.3, I will describe a number of these and show the cost that this convenience entails. Finally, in Section 21.4, I will focus on the interesting question of whether the anthropic approach to cosmology might lead to any *general* conclusions about how the study of cosmology will look in coming years.

21.2 Making predictions in a multiverse

Imagine that we have a candidate physical theory and a set of cosmological boundary conditions (hereafter denoted $\mathcal{T}$) that predict an ensemble of

physically realized systems, each of which is approximately homogeneous in some coordinates and can be characterized by a set of parameters (i.e. the constants appearing in the Standard Models of particle physics and cosmology). I assume here that the laws of physics themselves retain the same form. Let us denote each such system a ‘universe’ and the ensemble a ‘multiverse’. Given that we can observe only one of these universes, what conclusions can we draw regarding the correctness of $\mathcal{T}$, and how?

One possibility would be that there is a parameter for which *no* universes in the ensemble have the observed value. In this case, $\mathcal{T}$ would be ruled out. (Note that any $\mathcal{T}$ in which at least one parameter has an excluded range in *all* universes is thus rigorously falsifiable, which is a desirable feature for any theory.) Or perhaps some parameter takes only one value in all universes, and this value matches the observed one. This would obviously be a significant accomplishment of the theory. Both possibilities are good, as far as they go, and seem completely uncontroversial. But they do not go far enough. What if our observed parameter values appear in some but not all of the universes? Could we still rule out the theory if those values are incredibly rare, or gain confidence if they are extremely common?

I find it hard to see why not. If some theory predicts outcome A of some experiment with probability $p = 0.99999999$ and outcome B with probability $1 - p$, I think we would be reluctant to accept the theory if a single experiment were performed and showed outcome B, *even if we did not get to repeat the experiment*. In fact, it seems consistent with all normal scientific methodology to rule out the theory at 99.999999% confidence – the problem is just that we will not be able to *increase* this confidence without repeating our measurements. This seems to be exactly analogous to the multiverse situation *if* we can compute, given our $\mathcal{T}$, the *probability* that we should observe a given value for some observable.

Can we compute this probability distribution in a multiverse? Perhaps. I will argue that to do so, in a sensible way, we would need seven successive ingredients.

- (i) First, of course, we require a multiverse: an ensemble of regions, each of which would be considered a universe to observers inside it (i.e. its properties would be uniform for as far as those observers could see), but each of which may have different properties.
- (ii) Next we need to isolate the set of parameters characterizing the different universes. This might be the set of twenty or so free parameters in the Standard Model of particle physics (see refs. [2, 3] and references therein), plus a dozen or so cosmological parameters [4, 5]. There might

be additional parameters that become important in other universes, or differences (such as different forms of the physical laws) that cannot be characterized by differences in a finite set of parameters. But, for simplicity, let us assume that some set of numbers α_i (where $i = 1, \dots, N$) fully specifies each universe.

- (iii) Given our parameters, we need some *measure* with which to calculate their multi-dimensional probability distribution $P(\alpha_i)$. We might, for example, ‘count each universe equally’ to obtain the probability $P_U(\alpha_i)$, defined to be the chance that a randomly chosen universe from the ensemble would have the parameter values α_i .¹ This can be tricky, however, because it depends on how we delineate the universes. Suppose that $\alpha_1 = a$ universes happen to be 10^{10} times larger than $\alpha_1 = b$ universes. What would then prevent us from ‘splitting’ each $\alpha_1 = a$ universe into 10 or 100 or 10^{10} universes, thus radically changing the relative probability of $\alpha_1 = a$ versus $\alpha_1 = b$? These considerations might lead us to take a different measure, such as volume. We could then define $P_V(\alpha_i)$ as the chance that a random point in space resides in a universe with parameter values α_i . But in an expanding universe volume increases, so this would depend on the time at which we chose to evaluate the volume in each universe. We might then consider some ‘counting’ object that endures, say a baryon (which is relatively stable), and define $P_B(\alpha_i)$, the chance that a randomly chosen baryon resides in a universe with parameter values α_i . But now we have excluded from consideration universes with no baryons. Do we want to do that? This will be addressed in step (v). For now, note only that it is not entirely clear, even in principle, which measure we should place over our multiverse. We can call this the ‘measure problem’.
- (iv) Once we have chosen a measure object M , we still need actually to compute $P_M(\alpha_i)$, and this may be far from easy. For example, in computing P_V , some universes may have infinite volume. In this case, values of α_i leading to universes with finite volume will have zero probability. How, though, do we compare two infinite volumes? The difficulty can be seen by considering how we would count the fraction of red and blue marbles in an infinite box. We could pick one red, then one blue, and find a 50:50 split. But we could also repeatedly pick one red, then two blue, or five red, then one blue. We could do this forever and so obtain any ratio we like. What we would like to do is just ‘grab a bunch of marbles at random’ and count the ratio. However, in the multiverse

¹ Note that this is really shorthand for $(d\mathcal{P}/d\alpha_1 \cdots d\alpha_N)(d\alpha_1 \cdots d\alpha_N)$, the probability that α_i are all within the interval $[\alpha_i, \alpha_i + d\alpha_i]$, so $\mathcal{P}(\alpha_i)$ is a cumulative probability distribution.

case, it is not so clear how to pick this random ordering of marbles. This difficulty, which might be termed the ‘ordering problem’ [5], has been discussed in the context of eternal inflation [6–10] and a number of plausible prescriptions have been proposed. But there does not seem to be any generic solution or convincing way to prove that one method is correct.

- (v) If we have managed to calculate $P_M(\alpha_i)$, do we have a prediction? At least we have an answer to the question ‘Given that I am (or can associate myself with) a randomly chosen M -object, which sort of universe am I in?’ But this is *not* necessarily the same as the more general question ‘What sort of universe am I in?’ First, different M -objects will generally give different probabilities, so they cannot all be the answer to the same question. Second, we may not be all that closely associated with our M -object (which was chosen mainly to provide *some* way to compute probabilities) because it does not take into account important requirements for our existence. For example, if M were volume, I could ask ‘What should I observe, given that I am at a random point in space?’ However, we are *not* at a random point in space (which would on average have a density of 10^{-29} g cm $^{-3}$) but at one of the very rare points with density ~ 1 g cm $^{-3}$. The reason for this improbable situation is obviously ‘anthropic’ – we just do not worry about it because we can observe many other regions at the proper density. (If we could not see such regions, we might be more reluctant to accept a cosmological model with such a low average density.) Finally, it might be argued that the question we have answered through our calculation is not specific enough, because we know a lot more about the Universe than its volume or baryon content. We might, instead, ask: ‘Given that I am in a universe with the properties we have already observed, what should I observe in the future?’

As discussed at length in ref. [11], these different questions can be usefully thought of as arising from different choices of *conditionalization*. The probabilities $P_M(\alpha_i)$ are conditioned on as little as possible, whereas the anthropic question – ‘Given that I am a randomly chosen *observer*, what should I measure?’ – specifies probabilities conditioned on the existence of an ‘observer’. The approach of ‘Given what I know now, what will I see?’ specifies probabilities conditioned on being in a universe with all of the properties that we have already observed. These are three genuinely different approaches to making predictions in a multiverse that may be termed, respectively, ‘bottom-up’, ‘anthropic’ and ‘top-down’.

Let us denote by O the conditionalization object used to specify these conditional probabilities. In bottom-up reasoning it would be the same as the M -object; in the anthropic approach it would be an observer; and in the top-down approach it could be a universe with the currently known properties of our own. It can be seen that they cover a spectrum, from the weakest conditionalization (bottom-up) to the most stringent (top-down). Like our initial M -object, choosing a conditionalization is unavoidable and important, and there is no obviously correct choice to make. (See refs. [12] and [13] for similar conditionalization schemes.)

- (vi) Having decided on a conditionalization object O , the next step is to compute the number $N_{O,M}(\alpha_i)$ of O -objects per M -object, for each set of values of the parameters α_i . For example, if we have chosen to condition on observers, but have used baryons to define our probabilities, then we need to calculate the number of observers per baryon as a function of cosmological parameters. We can then calculate $P_O(\alpha_i) \equiv P_M(\alpha_i)N_{O,M}(\alpha_i)$, i.e. the probability that a randomly chosen O -object (observer) resides in a universe with parameters α_i . There are possible pitfalls in doing this. First, if $N_{O,M}$ is infinite, then the procedure clearly breaks down because P_O then becomes undefined. This is why the choice of the M -object should require as little as possible and hence be associated with the minimal-conditionalization bottom-up approach. This difficulty will occur generically if the existence of an O -object does not necessarily entail the existence of an M -object. For example, if the M -object were a baryon but the O -object were a bit of volume, then N would be infinite for α_i corresponding to universes with no baryons. The problem arises because baryons require volume but volume does not require baryons. This seems straightforward but becomes much murkier when we consider the *second* difficulty in calculating N , which is that we may not be able to define precisely what an O -object is or what it takes to make one. If we say that the O -object is an observer, what exactly does that mean? A human? A carbon-based life-form? Can observers exist without water? Without heavy elements? Without baryons? Without volume? It seems hard to say, so we are forced to choose some proxy for an observer, for example a galaxy or a star with planet, etc. But our probabilities will perforce depend on the chosen proxy, and this must be kept in mind.

It is worth noting a small bit of good news here. If we do manage to compute N_{O,M_1} consistently for some measure object M_1 , then insofar as we want to condition our probabilities on O -objects, we have solved

the measure problem. If we could consistently calculate N_{O,M_2} for a different measure object M_2 , then we should obtain the same result for N_O , i.e. $N_{O,M_1}P_{M_1} = N_{O,M_2}P_{M_2}$. Thus, our choice of M_1 (rather than M_2) becomes unimportant.

- (vii) The final step in making predictions is to assume that the probability that we will measure some set of α_i is given by the probability that a randomly chosen O -object will do so. This assumption really entails two others: first, that we are somehow directly associated with O -objects; second, that we have not – simply by bad luck – observed highly improbable values of the parameters. The assumption that we are *typical* observers has been termed the ‘principle of mediocrity’ [14]. One may argue about this assumption, but *some* assumption is necessary if we are to connect our computed probabilities to observations, and it is difficult to see what alternative assumption would be more reasonable.

The result of all this work would be the probability $P_O(\alpha_i)$ that a randomly selected O -object (out of all of the O -objects that exist in the multiverse) would reside in a universe governed by parameters α_i , along with a reason to believe that this same probability distribution should govern what we observe. We can then make observations or consider some already made ones. If the observations are highly improbable according to our predictions, we can rule out the candidate $\mathcal{T}$ at some confidence that depends on how improbable our observations were. Apart from the manifest and grave difficulties involved in actually completing the seven steps listed above in a convincing way, I think the only real criticism that can be levelled at this approach is that, unless $P = 0$ for our observed parameters, there will always be the chance that the $\mathcal{T}$ was correct and we measured an unlikely result. Usually, we can rid ourselves of this problem by repeating our experiments to make P as small as we like (at least in principle), but here we do not have that option – once we have ‘used up’ the measurement of all the parameters required to describe the Universe (which appears to be surprisingly few according to current theories), we are done.

21.3 Easing predictions in a multiverse: a bestiary of shortcuts

Although the idea of a multiverse has been around for a while, no one has ever really come close to making the sort of calculation outlined in the previous section.² Instead, those wishing to make predictions in a multiverse context have made strong assumptions about which parameters α_i actually vary

² The most ambitious attempt is probably the recent one by Tegmark [3,5].

across the ensemble, about the choice of O -object, and about the quantities $P_M(\alpha_i)$ and $N_{O,M}(\alpha_i)$ that go into predicting the measurement probabilities. Some of these short-cuts aim simply to make a calculation tractable; others are efforts to avoid anthropic considerations or, alternatively, to use anthropic considerations to avoid other difficulties.

I would not have listed any ingredients that I thought could be omitted from a sound calculation, so all of these short-cuts are necessarily incomplete (some, in my opinion, disastrously so). But by listing and discussing them, I hope to give a flavour of what sort of anthropic arguments have been made in the literature and where they may potentially go astray.

21.3.1 *Anthropic arguments only allow one set of parameters*

This assumption underlies a sort of anthropic reasoning that has earned the anthropic principle a lot of ill will. It goes something like this: ‘Let’s assume that lots of universes, governed by lots of different parameter values, exist. Then, since only universes with parameter values almost exactly the same as ours allow life, we must be in one of those, and we should not find it strange if our parameter values seem special.’ In the conventions I have described, this is essentially equivalent to setting O -objects to be observers and then hoping that the ‘hospitality factor’ $N_{O,M}(\alpha_i)$ is very narrowly peaked around one particular set of parameters. In this case, the *a priori* probabilities P_M are almost irrelevant because the shape of $N_{O,M}$ will pick out just one set of parameters. Because our observed values α_i^{obs} definitely allow observers, the allowed set must then be very near α_i^{obs} .

There are three problems with this type of reasoning. First, it is rather circular: it entails picking the O -object to be an observer, but then quickly substituting it with a ‘universe just like ours’, on the grounds that such universes will definitely support life.³ Thus we conclude that the universe should be very much like the observed one. The way to avoid this silliness is to allow at least the possibility that there are life-supporting universes with $\alpha_i \neq \alpha_i^{\text{obs}}$, i.e. to discard the unproven *assumption* that $N_{O,M}$ has a single, dominant, narrow peak.

The second problem is that, if $N_{O,M}$ were *so* narrowly peaked as to render P_M irrelevant, then we would be in serious trouble as theorists, because we would lose any ability to distinguish between candidates for our fundamental theory. Unless our observed universe is *impossible* in the theory, then the

³ One can also argue that, if there were other, more common, universes that supported life, we ought to be in them; since we are not, we should assume that almost all life-supporting universes are like our own. But this argument is also circular, since it assumes the anthropic argument works.

anthropic factor would force the predictions of the theory to match our observations. As discussed in Section 21.3.2, this is not good.

The third problem with $N_{O,M}$ being an extremely peaked function is that it does not appear to be true! As discussed below, for any reasonable surrogate for observers (for example galaxies like our own or stars with heavy elements, etc.), calculations using our current understanding of galaxy and structure formation seem to indicate that the region of parameter space in which there can be many of those objects may be small compared to the full parameter space but much larger than the region compatible with our observations.

21.3.2 *Just look for zero-probability regions in parameter space*

As mentioned in Section 21.2, one (relatively) easy thing to do with a multiverse theory is to work out which parameter combinations cannot occur in *any* universe. If the combination we actually observe is one of these, then the theory is ruled out. This is unobjectionable, but a rather weak way to test a theory because, if we are given two theories that are *not* ruled out, then we have no way of judging one to be better, even if the parameter values we observe are generic in one and absurdly rare in the other.⁴

This is not how science usually works. For example, suppose our theory is that a certain coin-tossing process is unbiased. If our only way to test this theory were to look for experimental outcomes that are impossible, then the theory would be unfalsifiable; we would have to accept it for *any* coin we are confronted with, because *no* sequence of tosses would be impossible! Even if 10 000 tosses in a row all came up heads, we would have no grounds for doubting our theory because, while getting heads 10 000 times in a row on a fair coin is absurdly improbable, it is not impossible. Nor would we have reason to prefer the (seemingly much better) ‘nearly every toss comes out heads’ theory. Clearly this is a situation we would like to improve on, as much in universes as in coin tosses.

21.3.3 *Let us look for overwhelmingly more probable values*

One possible improvement would be to employ the ‘bottom-up’ reasoning described in Section 21.2 and assume that we will observe a ‘typical’ set of parameters in the ensemble. This amounts to using the *a priori* (or

⁴ Amusingly, in terms of testing $\mathcal{T}$, the approach which makes *no* assumptions about $N_{O,M}$ is equivalent to the approach just described of making the very strong assumption that $N_{O,M}$ allows only one specific set of parameter values, because – in either case – a theory can only be ruled out if our observed values are impossible in that theory.

‘prior’) probabilities P_M for some choice of M -object, such as universes, and just ignoring the conditionalization factor $N_{O,M}$. There are two possible justifications for this. First, we might simply want to avoid any sort of anthropic issues on principle. Second, we might hope that some parameter values are much more common than others, to the extent that the $N_{O,M}$ factor becomes irrelevant, i.e. that P_M (rather than $N_{O,M}$) is very strongly peaked around some particular parameter values.

The problem with this approach is the ‘measure problem’ previously discussed: there is an implicit choice of basing probabilities on universes rather than on volume elements or baryons. Each of these measures has problems – for example, it seems that probabilities based on ‘universes’ depend on how the universes are delineated, which can be ambiguous. Moreover, there seems to be no reason to believe that predictions made using any two measures should agree particularly well. For example, as discussed elsewhere in this volume [15], in the string theory ‘landscape’ there are many possible parameter sets, depending on which metastable minimum one chooses in a potential that depends in turn on a number of fluxes that can take a large range of discrete values. Imagine that exponentially many more minima lead to $\alpha_1 = a$ than to $\alpha_1 = b$. Should we expect to observe $\alpha_1 = a$? Not necessarily, because the relative number of a and b universes that *actually come into existence* may easily differ exponentially from the relative number of a and b minima. (This seems likely to me in an eternal-inflation context, where the relative number of universes could depend on exponentially suppressed tunnellings between vacua.) Even worse, these may in turn differ exponentially (or even by an infinite factor) from the relative numbers of baryons or relative volumes.

In short, while we are free to use bottom-up reasoning with any choice of measure object we like, we are not free to assert that other choices would give similar predictions, or that conditionalization can be rendered irrelevant. So we had better have a good reason for our choice.

21.3.4 Let us fix some parameters as observed and predict others

Another way in which one might hope to circumvent anthropic issues is to condition the probabilities on some or all observations that have already been made. In this ‘top-down’ (or perhaps ‘pragmatic’) approach we ask: ‘Given everything that has been observed so far, what will we observe in some future measurement?’ This has a certain appeal, as this is often done in experimental science; we do not try to *predict* what our laboratory will

look like, just what will happen given that the laboratory is in a particular state at a given time. In the conventions of Section 21.2, the approach could consist of choosing the O -object to be universes with parameters agreeing with the measured values. While appealing, this approach suffers some deficiencies.

- It still does not completely avoid the measure problem, because even once we have limited our consideration to universes that match our current observations, we must still choose a measure with which to calculate the probabilities for the remaining ones.
- Through our conditioning, we may accept theories for which our parameter values are wildly improbable, without supplying any justification as to why we observe such improbable values. This is rather strange. Imagine that I have a theory in which the cosmological constant Λ is (with very high probability) much higher than we observe and the mass of the particle providing the dark matter m_{DM} almost certainly exceeds 1000 GeV. I condition on our observed Λ by simply accepting that I am in an unusual universe. Now, if I measured $m_{\text{DM}} = 1$ GeV, I would like to say my theory is ruled out. However, according to top-down reasoning, I should have already ruled it out if I had done my calculation in 1997, before Λ was measured. And someone who invented the very same theory next week – but had not been told that I have already ruled it out – would *not* rule it out, but instead just take the low value of m_{DM} (along with the observed Λ) as part of the conditionalization!
- If we condition on everything we have observed, we obviously give up the possibility of *explaining* anything through our theory.

These two issues motivate variations on the top-down approach in which only some current observations are conditioned on. Two possibilities are as follows.

- (i) We might *start* by conditioning on all observations, then progressively condition on less and less and try to ‘predict’ the things we have decided not to condition on (as well, of course, as any *new* observations) [16,17]. The more we can predict, the better our theory is. The problem is that either: (a) we will get to the point where we are conditioning on as little as possible (the bottom-up approach) and hence the whole conditionalization process will have been a waste of time; or (b) we will still have to condition on some things and admit that either these have an anthropic explanation or we just choose to condition on them (leading to the peculiar issues discussed above).

- (ii) We might choose at the outset to condition on things that we think may be fixed anthropically (without trying to generate this explanation), then try to predict the others [18]. This is nice in being relatively easy and in providing a justification for the conditionalization. It suffers from three problems: (a) we have to guess which parameters are anthropically important and which are not; (b) even if a parameter is anthropically unimportant, it may be strongly correlated in P_M with one that is; and (c) we still face the measure problem, which we cannot avoid by conditioning on observers, because we are avoiding anthropic considerations.

21.3.5 *Let us assume that just one parameter varies*

Most of the ‘short-cuts’ discussed so far have been attempts to avoid anthropic considerations. But we may, instead, consider how we might try to formulate an anthropic prediction (or explanation) for some observable, without going through the full calculation outlined in Section 21.2. The way of doing this that has been employed in the literature (largely in the efforts of Vilenkin and collaborators [19–21]) is as follows.

First, one fixes all but one of the parameters to the observed values. This is done for tractability and/or because one hopes that they will have non-anthropic explanations. Let us call the parameter that is allowed to vary across the ensemble α .

Second, an O -object is chosen such that – *given that only α varies* – the number $N_{O,M}$ of these objects (per baryon or comoving volume element) in a given universe is hopefully calculable and proportional to the number of observers. For example, if only Λ varies across the ensemble, galaxies might make reasonable O -objects because a moderately different Λ will probably not change the number of observers per galaxy, but *will* change the number of galaxies in a way that can be computed using fairly well understood theories of galaxy and structure formation (e.g. see refs. [5], [20] and [22]–[26]).

Third, it is assumed that $P_M(\alpha)$ is either flat or a simple power law, without any complicated structure. This can be done just for simplicity, but it is often argued to be natural [27–29]. The flavour of this argument is as follows. If P_M is to have an interesting structure over the relatively small range in which observers are abundant, there must be a parameter of order the observed α in the expression for P_M . But it is precisely the absence of this parameter that motivated the anthropic approach. For example, if the expression for $P_M(\Lambda)$ contained the energy scale ~ 0.01 eV corresponding to the observed Λ , the origin of that energy scale would probably be more

interesting than our anthropic argument, as it would provide the basis for a (non-anthropic) solution to the cosmological constant problem!

Under these (fairly strong) assumptions, we can then actually calculate $P_O(\alpha)$ and see whether or not the observed value is reasonably probable given this predicted distribution. For example, when Λ alone is varied, a randomly chosen galaxy is predicted to lie in a universe with Λ comparable to (but somewhat larger than) the value we see [23].⁵

I consider this sort of reasoning respectable, *given the assumptions made*. In particular, the anthropic argument in which *only* Λ varies is a relatively clean one. But there are a number of pitfalls when it is applied to parameters other than Λ or when one allows multiple parameters to vary simultaneously.

- Assuming that the abundance of observers is proportional to that of galaxies only makes sense if the number of galaxies – and not their properties – changes as α varies. However, changing nearly any cosmological parameter will change the properties of typical galaxies. For example, increasing Λ will decrease the number of galaxies, but will also make them smaller on average, because a high Λ squelches structure formation at the late times when massive galaxies form. Similarly, increasing the amplitude of primordial perturbations would lead to smaller, denser – but more numerous – galaxies, as would increasing the ratio of dark matter to baryons. In these cases, we must specify in more detail what properties an observer-supporting galaxy should have, and this is very difficult without falling into the circular argument that only galaxies like ours support life. Finally, this sort of strategy seems unlikely to work if we try to change *non-cosmological* parameters, as this could lead to radically different physics and the necessity of thinking *very* hard about what sort of observers there might be.
- The predicted probability distribution clearly depends on P_M , and the assumption that P_M is flat or a simple power law can break down. This can happen even for Λ [23, 30], but perhaps more naturally for other parameters – such as the dark matter density – for which particle physics models can already yield sensible values. Moreover, this breakdown is much more probable if (as discussed below and contrary to the assumption made above) the hospitality factor $N_{O,M}(\alpha)$ is significant over many orders of magnitude in α .
- Calculations of the hospitality factor $N_{O,M}(\alpha)$ can go awry if α is changed more than a little. For example, a neutrino mass slightly larger than

⁵ This is for a ‘flat’ probability distribution $dP_M/d\lambda \propto \lambda^\alpha$ with $\alpha = 0$. For $\alpha > 0$, higher values would be predicted; for $\alpha < 0$, lower values would be.

observed would suppress galaxy formation by erasing small-scale structure. But neutrinos with a large ($\gtrsim 100$ eV) mass would act as dark matter and lead to strong halo formation. Whether these galaxies would be hospitable is questionable, since they would be very baryon-poor, but the point is that the physics becomes *qualitatively* different. As another example, a lower photon/baryon ratio (n_γ/n_b) would lead to earlier, denser galaxies. But a *much* smaller value would lead to qualitatively different structure formation, as well as the primordial generation of heavy elements [4]; these changes are very dangerous because, over orders of magnitude in α , $P_M(\alpha)$ will tend to change by many orders of magnitude. Thus, even if these alternative universes only have a few observers in them, they may dominate P_O and hence qualitatively change the predictions.

- Along the same lines, but perhaps even more pernicious, when multiple parameters are varied simultaneously, the effects of some variations can offset the effect of others so that universes quite different from ours can support many of our chosen O -objects. For example, increasing Λ cuts off galaxy formation at a given cosmic density, but raising Q (the amplitude of the presumably scale-invariant perturbations on the horizon scale) causes galaxies to form earlier, thus nullifying the effect of Λ . This can be seen in the calculations of refs. [24] and [31] and is discussed explicitly in refs. [3]–[5] and [26]. Many such degeneracies exist, because raising Λ , n_γ/n_b or the neutrino mass all decrease the efficiency of structure formation, while raising the density ρ_{DM} of dark matter relative to the density ρ_b of baryons, or raising Q , would increase the efficiency. As an extreme case, it was shown in ref. [4] that, if Q and n_γ/n_b are allowed to vary with Λ , then universes in which Λ is 10^{17} times our observed value could arguably support observers! Including more cosmological or non-cosmological parameters can only make this problem worse.

These problems indicate that, while anthropic arguments concerning Λ in the literature are relatively ‘clean’, it is unclear whether other parameters (taken individually) will work as nicely. More importantly, a number of issues arise when several parameters are allowed to vary at once, and there does not seem to be any reason to believe that success in explaining one parameter anthropically will persist when additional parameters are allowed to vary. It may do so in some cases – for example, allowing neutrino masses to vary in addition to Λ does not appear to spoil the anthropic explanation of a small but non-zero Λ [25]. On the other hand, allowing Q to vary does unless $P_M(Q)$ is strongly peaked at small values [26]. I suspect that allowing ρ_{DM}/ρ_b or n_γ/n_b to vary along with Λ would have a similar effect.

21.3.6 So what should we do?

For those serious about making predictions in a multiverse, I would propose that rather than working to generate additional incomplete anthropic arguments by taking short-cuts, a much better job must be done with each of the individual ingredients. For example, our understanding of galaxy formation is sufficiently strong that the multi-dimensional hospitality factor $N_{O,M}(\alpha_i)$ could probably be computed for α_i within a few orders of magnitude of the observed values, if we take the O -objects to be galaxies with properties in some range. Second, despite some nice previous work, I think the problem of how to compute P_M in eternal inflation is an open one. Finally, the currently popular string/M-theory landscape cannot hope to say much about P_M until its place in cosmology is understood – in particular, we need a better understanding both of the statistical distribution of field values that result from evolution in a given potential and of how transitions between vacua with different flux values occur and exactly what is transitioning.

21.4 Are there general predictions of anthropic reasoning?

The preceding sections might suggest that it will be a huge project to compute sound predictions of cosmological and physical parameters from a multiverse theory in which they vary. It may indeed be a long time before any such calculation is believable. It is therefore worth asking if there is any way nature might indicate whether the anthropic approach is sensible, i.e. does it make any *general* predictions, even without the full calculation of P_O ? Interestingly, I think the answer might be yes; I am aware of two such general (though somewhat vague) predictions of the anthropic approach.

To understand the first, assume that only one parameter, α , varies and consider $p(\log \alpha) = \alpha P_M(\alpha)$, the probability distribution in $\log \alpha$, given by some theory $\mathcal{T}$. For $\log \alpha$ near the observed value $\log \alpha^{\text{obs}}$, p can either rise, fall or remain approximately constant with increasing $\log \alpha$. In the first two cases, $\mathcal{T}$ would predict that we should see a value of α that is, respectively, higher or lower than we actually do *if* no anthropic conditionalization $N_{O,M}$ is applied. Now suppose we somehow compute $N_{O,M}(\alpha)$ and find that it falls off quickly for values of α much smaller or larger than we observe, i.e. that only a range $\alpha_{\min} \lesssim \alpha \lesssim \alpha_{\max}$ is ‘anthropically acceptable’. Then we have an anthropic argument explaining α^{obs} , because this fall-off means that P_O will only be significant near α^{obs} . But now note that *within* the anthropically acceptable range, P_O will be peaked near $\alpha_{\max}$ if p is increasing with α , or near $\alpha_{\min}$ if p is decreasing with α . That is, we should expect α^{obs} at

one edge of the anthropically acceptable range. This idea has been called the ‘principle of living dangerously’ [32]. It asserts that, for a parameter that is anthropically determined, we should expect that a calculation of $N_{O,M}$ would reveal that observers would be strongly suppressed either for α slightly larger or slightly smaller than α^{obs} , depending on whether p is rising or falling.

Now this is not a very specific prediction; exactly where we would expect α^{obs} to lie depends on both the steepness of $p(\log \alpha)$ and the sharpness of the cut-off in $N_{O,M}$ for α outside the anthropically acceptable range. And it would not apply to anthropically determined parameters in all possible cases. (For example, if p were flat near α^{obs} but very high at $\alpha \gg \alpha^{\text{obs}}$, anthropic effects would be required to explain why we do not observe the very high value; but any region within the anthropically acceptable range would be equally probable, so we would not expect to be living on the edge.) Despite these caveats, this is a prediction of sorts, because the naïve expectation would probably be for our observation to place us somewhere in the interior of the region of parameter space that is hospitable to life rather than at the edge.

A second sort of general prediction of anthropic reasoning is connected to what might be called ‘cosmic coincidences’. For example, many cosmologists have asked why the current density in vacuum energy, dark matter, baryons and neutrinos are all within a couple of orders of magnitude of each other – making the Universe a much more complicated place than it might be. Conventionally, it has been assumed that these are just coincidences which follow directly from fundamental physics that we do not understand. But if the anthropic approach to cosmology is correct (that is, if it is the real answer to the question of why these densities take the particular values they do), then the explanation is quite different; the densities are bound together by the necessity of the existence of observers, because only certain combinations will do.

More explicitly, suppose several cosmological parameters are governed by completely unrelated physics, so that their individual prior probabilities P_M simply multiply to yield the multi-dimensional probability distribution. For example, we might have $P_M(\Lambda, \Omega_{\text{DM}}/\Omega_b, Q) = P_M(\Lambda)P_M(\Omega_{\text{DM}}/\Omega_b)P_M(Q)$. But even if P factors like this, the hospitality factor $N_{O,M}$ will almost certainly not do so; if galaxies are O -objects, the number of galaxies formed at a given Λ will depend on the other two parameters and only certain combinations will give a significant number of observers. Thus, $P_O = N_{O,M}P_M$ will likewise have correlations between the different parameters that lead to only particular combinations (e.g. those with $\Omega_{\text{DM}}/\Omega_b \sim 1\text{--}10$ for a

given Q and Λ) having high probabilities. The cosmic coincidences would be explained in this way.

This anthropic explanation of coincidences, however, should not only apply to things that we have already observed. If it is correct, then it should apply also to *future* observations; that is, we should expect to uncover yet more bizarre coincidences between quantities that seem to follow from quite unrelated physics.

How might this actually happen? Consider dark matter. We know fairly precisely how much dark matter there is in the Universe and what its basic properties are. But we have no idea what it is, and many possible candidates have been proposed. In fact, we have no *observational* reason to believe that dark matter is one substance at all; in principle, it could be equal parts axions, supersymmetric particles and primordial black holes. The reason most cosmologists do not expect this is that it would be a strange coincidence if three substances involving quite independent physics all had roughly the same density. But, of course, this would be just like the suprising-but-true coincidences that already hold in cosmology.

In the anthropic approach, the comparability of these densities could be quite natural [11]. To see why, imagine that there are two *completely independent* types of dark matter permeating the ensemble; in each universe, they have particular densities ρ_1 and ρ_2 out of a wide range of possibilities, so that the densities in a randomly chosen universe (or around a randomly chosen baryon, etc.) will be given probabilistically by $P_M(\rho_1)P_M(\rho_2)$. Under these assumptions, there is no reason to expect that we should observe $\rho_1 \sim \rho_2$ based just on these *a priori* probabilities. However, now suppose that $N_{O,M}$ picks out a particular narrow range of *total* dark matter density as anthropically acceptable – that is, $N_{O,M}(\rho_1 + \rho_2)$ is narrowly peaked about some ρ_{anth} . In this case, the peak of the probability distribution $P_O(\rho_1, \rho_2)$ will occur where $P_M(\rho_1)P_M(\rho_2)$ is maximized *subject to the condition* that $\rho_1 + \rho_2 \simeq \rho_{\text{anth}}$. For simplicity, let both prior probabilities be power laws: $P_M(\rho_1) \propto \rho_1^\alpha$ and $P_M(\rho_2) \propto \rho_2^\beta$. Then it is not hard to show that, if $\alpha \geq 0$ and $\beta \geq 0$, then the maximum probability will occur when $\rho_1/\rho_2 = \alpha/\beta$. That is, the two components are likely to have similar densities unless the *power law indices* of their probability distributions differ by orders of magnitude.⁶ Of course, there are many ways in which this coincidence could fail to occur (e.g. negative power law indices or correlated probabilities), but the point is that there is a quite natural set of circumstances in which the

⁶ Extremely high power law indices are uncomfortable in the anthropic approach because they would lead to P_O being peaked where $N_{O,M}$ is declining, i.e. we should be living *outside* the anthropically comfortable range – not just dangerously but recklessly.

components are coincident, even though the *fundamental* physics is completely unrelated.

21.5 Conclusions

The preceding sections should have convinced the reader that there are good reasons for scientists to be very worried if we live in a multiverse; in order to test a multiverse theory in a sound manner, we must perform a fiendishly difficult calculation of $P_O(\alpha_i)$, the probability that an O -object will reside in a universe characterized by parameters α_i . And, because of the shortcomings of the short-cuts one may (and presently must) take in doing this, almost any particular multiverse prediction is going to be easy to criticize. Much worse, we face an unavoidable and important choice in what O should be: a possible universe, an existing universe, a universe matching current observations, a bit of volume, a baryon, a galaxy, an ‘observer’ etc.

I find it disturbingly plausible that observers really are the correct conditionalization object, that their use as such is the correct answer to the measure problem, and that anthropic effects are the real explanation for the values of some parameters (just as for the local density that we observe). Many cosmologists appear to believe that taking the necessity of observers into account is shoddy thinking, employed only because it is the *easy* way out of solving problems the ‘right’ way. But the arguments of this chapter suggest that the truth may well be exactly the opposite; the anthropic approach may be the right thing to do in principle, but nearly impossible in practice.

Even if we cannot calculate P_O in the foreseeable future, however, cosmology in a multiverse may not be completely devoid of predictive power. For example, if anthropic effects are at work, they should leave certain clues. First, if we could determine the region of parameter space hospitable to observers, we should find that we are living on the outskirts of the habitable region rather than somewhere in its middle. Second, if the anthropic effects are the explanation of the parameter values – and coincidences between them – that we see, then it ought to predict that new coincidences will be observed in future observations.

If, in the next few decades, dark matter is resolved into several equally important components, dark energy is found to be three independent substances, and several other ‘cosmic coincidences’ are observed, even some of the most die-hard sceptics might accede that the anthropic approach may have validity – why else would the Universe be so baroque? On the other hand, if the specification of the basic cosmological constituents is essentially complete, and the associated parameters are in the middle of a relatively

large region of parameter space that might arguably support observers, then I think the anthropic approach would lose almost all its appeal. We would be forced to ask why the universe is not much weirder.

References

- [1] M. Rees. *Just Six Numbers* (New York: Basic Books, 2000).
- [2] C. J. Hogan. Why the universe is just so. *Rev. Mod. Phys.* **72** (2000), 1149 [astro-ph/9909295].
- [3] M. Tegmark, A. Aguirre, M. J. Rees and F. Wilczek. Dimensionless constants, cosmology and other dark matters. *Phys. Rev. D* **73** (2006), 23505 [astro-ph/0511774].
- [4] A. Aguirre. The cold big-bang cosmology as a counter-example to several anthropic arguments. *Phys. Rev. D* **64** (2001), 83508.
- [5] M. Tegmark. What does inflation really predict? *J. Cosmol. Astropart. Phys.*, **0504** (2005), 001 [astro-ph/0410281].
- [6] A. D. Linde and A. Mezhlumian. On regularization scheme dependence of predictions in inflationary cosmology. *Phys. Rev. D* **53** (1996), 4267 [gr-qc/9511058].
- [7] V. Vanchurin, A. Vilenkin and S. Winitzki. Predictability crisis in inflationary cosmology and its resolution. *Phys. Rev. D* **61** (2000), 083507 [gr-qc/9905097].
- [8] A. H. Guth. Inflation and eternal inflation. *Phys. Rep.* **333** (2000), 555 [astro-ph/0002156].
- [9] J. Garriga and A. Vilenkin. A prescription for probabilities in eternal inflation. *Phys. Rev. D* **64** (2001), 023507 [gr-qc/0102090].
- [10] J. Garriga, D. Schwartz-Perlov, A. Vilenkin and S. Winitzki. Probabilities in the inflationary multiverse. *J. Cosmol. Astropart. Phys.*, **0601** (2006), 017 [hep-th/0509184].
- [11] A. Aguirre and M. Tegmark. Multiple universes, cosmic coincidences, and other dark matters. *J. Cosmol. Astropart. Phys.*, **0501** (2005), 003 [hep-th/0409072].
- [12] N. Bostrum. *Anthropic Bias: Observation Selection Effects in Science and Philosophy* (New York: Routledge, 2002).
- [13] J. B. Hartle. Anthropic reasoning and quantum cosmology. *AIP Conf. Proc.*, **743** (2005), 298 [gr-qc/0406104].
- [14] A. Vilenkin. Predictions from quantum cosmology. *Phys. Rev. Lett.* **74** (1995), 846 [gr-qc/9406010].
- [15] L. Susskind. This volume (2007) [hep-th/0302219].
- [16] S. W. Hawking and T. Hertog. Why does inflation start at the top of the hill? *Phys. Rev. D* **66** (2002), 123509 [hep-th/0204212].
- [17] A. Albrecht. Cosmic inflation and the arrow of time. In *Science and Ultimate Reality*, eds. J. D. Barrow, P. C. W. Davies and C. L. Harper (Cambridge: Cambridge University Press, 2004), pp. 363–401 [astro-ph/0210527].
- [18] M. Dine. Supersymmetry, naturalness and the landscape. In *Pascos 2004, Themes in Unification* (Singapore: World Scientific, 2004), pp. 249–63 [hep-th/0410201].
- [19] J. Garriga and A. Vilenkin. Anthropic prediction for Lambda and the Q catastrophe. *Prog. Theor. Phys. Suppl.* **163** (2005), 245 [hep-th/0508005].

- [20] M. Tegmark, A. Vilenkin and L. Pogosian. Anthropic predictions for neutrino masses. *Phys. Rev. D* **71** (2005), 103523 [astro-ph/0304536].
- [21] J. Garriga and A. Vilenkin. Testable anthropic predictions for dark energy. *Phys. Rev. D* **67** (2003), 043503 [astro-ph/0210358].
- [22] J. Garriga, M. Livio and A. Vilenkin. The cosmological constant and the time of its dominance. *Phys. Rev. D* **61** (2000), 023503 [astro-ph/9906210].
- [23] J. Garriga and A. Vilenkin. On likely values of the cosmological constant. *Phys. Rev. D* **61** (2000), 083502 [astro-ph/9908115].
- [24] J. Garriga and A. Vilenkin. Solutions to the cosmological constant problems. *Phys. Rev. D* **64** (2001), 023517 [hep-th/0011262].
- [25] L. Pogosian, A. Vilenkin and M. Tegmark, Anthropic predictions for vacuum energy and neutrino masses. *J. Cosmol. Astropart. Phys.*, **0407** (2004), 005 [astro-ph/0404497].
- [26] M. L. Graesser, S. D. H. Hsu, A. Jenkins and M. B. Wise. Anthropic distribution for cosmological constant and primordial density perturbations. *Phys. Lett. B* **600** (2004), 15 [hep-th/0407174].
- [27] A. Vilenkin. Quantum cosmology and the constants of nature. In *Tokyo 1995, Cosmological Constant and the Evolution of the Universe* (Tokyo: Universal Academy Press, 1995), pp. 161–8 [gr-qc/9512031].
- [28] S. Weinberg. *A priori* probability distribution of the cosmological constant. *Phys. Rev. D* **61** (2000), 103505 [astro-ph/0002387].
- [29] L. Smolin. This volume (2007) [hep-th/0407213].
- [30] D. Schwartz-Perlov and A. Vilenkin. Probabilities in the Bousso–Polchinski multiverse. *J. Cosmol. Astropart. Phys.* **6** (2006), 010 [hep-th/0601162].
- [31] M. Tegmark and M. J. Rees. Why is the CMB fluctuation level 10^{-5} ? *Astrophys. J.* **499** (1998), 526 [astro-ph/9709058].
- [32] S. Dimopoulos and S. Thomas. Discretuum versus continuum dark energy. *Phys. Lett. B* **573** (2003), 13 [hep-th/0307004].

22

Multiverses: description, uniqueness and testing

George Ellis

Department of Applied Mathematics, University of Cape Town

22.1 Introduction

The idea of a multiverse – an ensemble of universes or expanding domains like the one we see around us – has recently received increasing attention in cosmology. It has been conceived of as occurring either in separate places or times in the same overall encompassing universe (as in chaotic inflation) or through splitting of the quantum wave-function (as in the Everett interpretation of quantum mechanics) or as a set of totally disjoint universes, with no causal connection whatsoever. Physical properties may be different in the different universes or in different expanding domains within a single universe.

In this context, definitions are important. Some workers refer to the separate expanding regions in chaotic inflation as ‘universes’, even though they have a common causal origin and are all part of the same single spacetime. In keeping with long established use, I prefer to use the word ‘universe’ to refer to the single unique connected spacetime of which our observed region (centred on our galaxy and bounded by our visual horizon in the past) is a part. I will describe situations such as chaotic inflation – with many expanding domains – as a ‘multi-domain universe’. Then we can reserve the term ‘multiverse’ for a collection of genuinely disconnected spacetimes, which are not causally related. When the discussion pertains to both disjoint collections of universes and different domains of a multi-domain universe, I will refer to an ‘ensemble of universe domains’ or ‘ensemble’ for short. There are basically three motivations for proposing an ensemble.

Generating mechanisms

It has been claimed that a multi-domain universe is the inevitable outcome of the physical processes that generated our own expanding region from a primordial quantum configuration; they would therefore have generated

many other such regions. This was first modelled in a specific way by Vilenkin [1] and then developed by Linde [2,3] in his chaotic cosmology scenario. Since then, many others – including Sciama [4], Leslie [5], Deutsch [6], Tegmark [7, 8], Smolin [9], Lewis [10], Weinberg [11], Rees [12, 13] and Davies [14] – have discussed ways in which an ensemble of universe domains might originate physically.

Universality

The existence of an ensemble can be seen as the result of an overall philosophical stance underlying physics: the idea that ‘everything that can happen does happen’ [4,8,15]. This is a logical conclusion of the Feynman path integral approach to quantum theory, viewed as a basic underlying physical principle that provides a foundation for quantum physics and, in some sense, a fundamental approach to the nature of existence. Clearly this implies that we consider all possible alternative physics, as well as all possible alternative spacetime geometries.

Fine-tuning and anthropic issues

An ensemble has been proposed as an explanation for the way that our universe appears to be anthropically fine-tuned for the existence of life and the appearance of consciousness. It is now clear that, if any of a number of parameters which characterize the observed universe – including both fundamental constants and initial conditions – were slightly different, no complexity of any sort would come into existence and hence no life would appear and no Darwinian evolution would take place [16,17]. For example, Rees [18] suggests there are just six numbers that must be fine-tuned in order that life can exist:

- (1) N = ratio of electrical and gravitational forces between protons = 10^{36} ;
- (2) E = nuclear binding energy as a fraction of rest mass energy = 0.007;
- (3) Ω = amount of matter in universe in units of critical density = 0.3;
- (4) Λ = cosmological constant in units of critical density = 0.7;
- (5) Q = amplitude of density fluctuations for cosmic structures = 10^{-5} ;
- (6) D = number of spatial dimensions = 3.

A multiverse seems to be the only scientific way of explaining the precise adjustment of all these parameters simultaneously, so that complexity and life eventually emerged. The existence of a sufficiently large collection of expanding domains, covering the full range of possible combinations of parameter values, ensures that in some of them life would arise. In most of the domains, it will not do so because conditions will be wrong. But in a

few of them conditions will happen to work out right. So, although there is an incredibly small probability of a domain existing that will allow life, if there exist enough domains, it becomes essentially inevitable that somewhere the right mix of circumstances will occur. If physical cosmogonic processes naturally produced such a variety of expanding domains, we necessarily find ourselves in one in which all the many conditions for life have been fulfilled.

This is analogous to the way in which we look upon the special character of the Solar System. We do not agonize about how initial conditions for the Earth and Solar System have allowed life to emerge. We realize that the Solar System is one of hundreds of billions of planetary systems in the Milky Way and accept that (though the probability of any one of them being bio-friendly is very low) at least a few will naturally be so. No direct fine-tuning is required, provided we take for granted both the nature of the laws of physics and the specific initial conditions in the universe. The processes of star formation throughout our galaxy naturally lead to the generation of the full range of possible stellar systems and planets.

An important point is that, in order for an ensemble with varied properties to explain fine-tuning, it must be an *actually existing ensemble* and not a potential or hypothetical one.¹ This is essential for any such anthropic argument.

Combinations of the above

One may finally note that these motivations are not necessarily in conflict with each other; one might, for example, attempt to propose a generating mechanism based on the ideas of universality that will also provide an anthropic explanation.

22.2 Describing multiverses

In considering how multiverses should be defined, it is important to note the key distinction between the collection of all possible universes and ensembles of really existing universes [20, 21]. We need first to describe the space of possibilities, characterizing the kinds of universes or expanding domains that can exist in any of the ensembles envisaged, and then to specify a distribution function on that space, characterizing those that actually exist in a specific realized ensemble.

¹ An example of a paper that apparently only considers hypothetical ensembles is the contribution by Bjorken to this volume [19]. Although he talks about ‘constructing ensembles’, we are regrettably unable to do this.

22.2.1 Spaces of possibilities

The ‘possibility space’ M is the set of all possible universes m , each of which can be described by a set of states s in a state space S . Each universe will be characterized by a set of distinguishing parameters p , which are coordinates in S . The set of all possible parameters p form a parameter space P . One of the issues that arises is the ‘equivalence problem’ – the same universe m will in general be represented by a variety of different parameters. One can either factor out these multiple representations, going to the corresponding quotient space where each universe is represented just once, or try to identify the different representations of the same space in a naturally occurring parameter space. The latter is the better option, because the quotient space does not have a good manifold structure.

Each universe m in M will evolve from its initial state to the final state according to the dynamics operative, with some or all of its parameters varying as it does so. Thus, each such path in S (in degenerate cases, a point) is representative of one of the universes in M . If an ensemble contains numerous different FLRW-like² domains within a single overall connected spacetime, we can characterize the properties of each of these expanding domains by such a description.

The very description of the space M of possibilities is based on an assumed set of laws of behaviour – either laws of physics or meta-laws that determine the laws of physics. Without this, we have no basis for setting up a description of S . Indeed, these regularities are characterized by the parameters p used to describe these spaces. These parameters belong to various categories, which we now list. We denote them as $p_j(i)$, where j indicates the category and i denotes the parameter itself.

Physics parameters

- $p_1(i)$ are the basic physics parameters within each universe, excluding gravity. These characterize the non-gravitational laws of physics and related constants (e.g. the fine-structure constant) and parameters describing basic particle properties (mass, charge, spin, etc.) They should be dimensionless, or one may be describing the same physics in other units.
- $p_2(i)$ are the parameters describing the cosmological (gravitational) dynamics, e.g. $p_2(1) = 1$ indicates that Einstein gravity dominates, $p_2(1) = 2$ indicates that Brans–Dicke theory dominates, $p_2(1) = 3$ indicates that electromagnetism dominates, etc. Associated with each choice

² FLRW = Friedmann–Lemaître–Robertson–Walker.

are the relevant parameter values, e.g. $p_2(2) = G$, $p_2(3) = \Lambda$ and $p_2(4) = \omega$ in the Brans–Dicke case. If gravity can be derived from more fundamental physics in some unified theory, these will be related to the parameters $p_1(i)$. For example, Λ may be determined from quantum field theory and basic matter parameters.

Cosmological parameters

- $p_3(i)$ are the cosmological parameters characterizing the matter content of a universe. These encode the presence of radiation, baryonic matter, dark matter, neutrinos, scalar fields, etc. In each case, we must specify the relevant equations of state and the auxiliary functions needed to determine the physical behaviour of matter (e.g. a barotropic equation of state for a fluid or the potential for a scalar field). These are characterizations of the macro-states of matter arising out of fundamental physics, so the possibilities here will be related to the parameters in $p_1(i)$.
- $p_4(i)$ are the geometrical parameters characterizing the spacetime geometry of the cosmological solutions envisaged, e.g. in the standard FLRW models, the scale factor $a(t)$, Hubble parameter $H(t)$ and spatial curvature k . These parameters will be related to the amount of each type of matter, characterized by $p_3(i)$ through the gravitational equations specified in $p_2(i)$. For example, Einstein's field equations relate the Hubble parameter and density parameters to the spatial curvature. One of the key issues is how the FLRW models, providing very good representations of the region we actually observe, relate to more generic models. This cannot be investigated within the context of FLRW models alone, since these are extremely special geometrically. More general models will contain anisotropy and inhomogeneity, so we must include spacetime functions characterizing the shear, vorticity and spatial density variations, as well as their dynamic behaviour [22, 23]. We also have to characterize all possible global spacetime connectivities, e.g. the many possible topologies of the space sections in FLRW universes.

Parameters relating to existence of life

- $p_5(i)$ are the parameters related to the functional emergence of complexity in the hierarchy of structure, e.g. the existence of chemically complex molecules which provide the foundations for life. Thus $p_5(1)$ might be the number of different types of atoms (as specified in the periodic table), $p_5(2)$ the number of different states of matter (crystal, glass, liquid, gas, plasma) and $p_5(3)$ the number of different types of molecules, characterized in a suitable way. These are properties emerging out of the

fundamental physics in operation, and so are related to the parameter set $p_1(i)$ [24]. Since we are considering physics quite different from that experienced on Earth, we cannot take any of these properties for granted.

- $p_6(i)$ are the biologically relevant parameters related specifically to the functional emergence of life and consciousness. For example, $p_6(1)$ might characterize the possibility of supra-molecular chemistry and $p_6(2)$ the possibility of living cells. This builds on the complexity allowed by $p_5(i)$ and again relates to the parameter set $p_1(i)$. However, when considering altered physics, we do not know what the necessary or sufficient conditions for intelligent life are. Thus we cannot at present fully characterize these parameters.

Choices have to be made for all these parameter sets on some basis, be it physical or philosophical. Major issues arise and these determine the nature of the ensembles envisaged. In particular, one must first address the following fundamental issue.

Issue (1) What determines the possibility space M ? What range of possibilities will be contemplated? Where does this structure come from?

What is the meta-cause that delimits this set of possibilities? Whatever choice we make, the question will arise of why we only consider this range of options. Have we really considered the full range of possibilities? What is it that determines that range?

22.2.2 *Realized multiverses*

Given a description of the set of possibilities, the issue then is which of them occur in reality. This is described by a distribution function and a measure.

The distribution function

To describe a physically realized multiverse or ensemble, we need to define a distribution function $f(m)$ on M , specifying how many times each type of possible universe m is realized in the ensemble. The class of models comprising the ensemble is determined by all the parameters held constant across the ensemble; we call these ‘class parameters’. The set of models occurring within the class is then determined by the parameters allowed to vary; we call these ‘member parameters’. If a realized universe contains numerous different FLRW-like expanding domains within a single spacetime, each evolving separately from the others, we can characterize the ensemble by a

distribution function for the FLRW parameters of these causally separated domains.

A measure

For continuous parameters, as a counterpoint to the distribution function, we need a volume element $\pi = \Pi_{i,j} m_{ij}(m) dp_j(i)$ on the parameter space, characterised by weights $m_{ij}(m)$. The number of universes corresponding to the set of parameter increments $dp_j(i)$ will then be given by $dN = f(m)\pi$. We can also find the average value of any physical quantity from f and π . However, the obvious choices for the measure may not be the best ones. Indeed, what looks best is highly coordinate-dependent and can be changed arbitrarily by choosing new coordinates. Furthermore, the resulting integrals may often diverge. How to choose an optimal measure remains an open question, even in the FLRW case [25], and the use of ensembles is not well defined until this is clarified. This is a mathematical issue, but it has important physical implications.

Thus, a realized ensemble E of universes is characterized by a possibility space M , together with a measure π and distribution function $f(m)$ on M . Another major issue arises here, and this determines the nature of the ensembles claimed actually to exist.

Issue (2) What determines the distribution function $f(m)$? What is the meta-cause that delimits the set of realizations out of the set of possibilities?

The answer to this has to be different from the answer to Issue 1, because here we are describing the contingency of selection of a subset of possibilities for realization from the total set of possibilities – determination of the latter being what is considered in Issue 1. Whatever choice we make, the following question will arise: Why has this particular set of universes or expanding domains come into being? What kind of meta-cause could be in operation here? Some choices will correspond to an actually existing multiverse and others to one or more multi-domain universes.

22.3 Issues arising

Several major physical and philosophical issues arise in considering ensembles of universes: (1) their non-uniqueness; (2) the emergence of self-consciousness; (3) whether fine-tuning or generic primordial conditions is more likely; (4) the question of realized infinities; (5) the source of regularities. We now consider these in turn.

22.3.1 *Non-uniqueness*

The first important point is that a multiverse or ensemble is not a unique concept; there can be many quite different realizations. Saying that everything that can happen does happen will not specify a unique multiverse for two reasons.

Non-uniqueness in realized models

Given the space of possibilities, realized multiverses are by no means unique. Their description requires the existence of a well defined and physically motivated distribution function $f(m)$ on the space of all possible universes. The mere fact that different distribution functions are possible shows that the concept of an ensemble is not unique. Hence one has to ask: How does the choice of these functions originate and what is their rationale?

These questions can be partially answered scientifically. A really existing ensemble of universes or domains may arise from the operation of a generating process, which adequately explains the origin of its member and their ranges of characteristics and parameter distribution from a more fundamental potential or primordial quantum configuration. That is, there may be a specific generating process which determines $f(m)$.

However, when it comes to the question of what is responsible for the operation of a specific generating process rather than some other one which would generate a different ensemble, an adequate answer cannot be given scientifically. This is the question of why the primordial dynamics leading to the given existing ensemble of universes is of one type rather than another. Even if we could establish $f(m)$ in detail, it is difficult to imagine how we would scientifically explain why one generating process (operating prior to the existence of the universe) was instantiated rather than some other one. The only possible answer comes from philosophical considerations. *A priori*, there is a complete arbitrariness in the resultant models because the generating process is not uniquely determined by any provable principle.

Non-uniqueness of possible models

The ‘space of all possible universes’ is not an easily delimited or unique concept, but the choice of what is included here determines what kind of multiverse can exist. How wide a variation of properties are we prepared to consider in our class of multiverses? Are we prepared to consider: universes with quite different physics (e.g. not coming from a variational principle and not based on quantum field theory); universes with different kinds of logic

and perhaps alternative forms of mathematics; universes allowing magic, such as envisaged in the Harry Potter novels by J. K. Rowling?

If we are not prepared to allow such situations, what is the rationale for this? If the underlying principle is that ‘all that can happen does happen’, then there should conceivably be universes of all these kinds, as well as theistic and non-theistic ones, universes based in beauty and ethereal vibrations rather than physics, etc. Science fiction provides a fruitful source of such ideas. We surely cannot even conceive of all the alternatives, much less write them down systematically. In many of these classes of universes, no processes generating expanding domains would be possible, because the requisite kind of physics would not be realized. If any such possibilities are to be excluded, we have to be given both a meta-principle excluding them and a justification as to why that meta-principle should apply in the ensemble. Only philosophy can justify such a choice.

Implications of non-uniqueness

We conclude that the idea of a multiverse or ensemble is not a unique concept but a whole package of differing possibilities. This has several implications. First, it is not necessarily true that life can exist in any universe in an ensemble; this may or may not be true. Second, in considering experimental or observational tests for the existence of an ensemble, one needs to be told *which specific kind of ensemble is claimed to exist* and how to test that claim. How can we observationally or experimentally exclude specific classes of multiverse, e.g. those in which there may be any number of copies of our own universe. Thus one question would be: How do you determine how many copies of our own universe exist in any claimed ensemble?

22.3.2 The emergence of consciousness

Related to this question is the fact that we do not know the sufficient conditions for the emergence of consciousness. Given the kind of physics which holds here and now, necessary conditions for life as we know it depend on suitable choices of parameters in fundamental physics [7, 24]. However, we would have no handle on how to deal with this issue if physics were substantially different. Indeed, we do not even know what the necessary conditions are within the broad kind of physics that holds here and now. Hence we cannot properly characterize the domains in any ensemble where intelligent life may be able to exist. We have a good idea of many *necessary* conditions, but we do not know the *sufficient* conditions.

22.3.3 *Special or general*

An ensemble may include singular and non-singular, as well as special and general, universes. Which is more fundamental and so more likely to occur: fine-tuning to produce the very special initial conditions for our observed universe³ or generic primordial conditions? While the introduction of ensembles has in effect been driven by the second view, they can equally well fulfil the first, the difference between them coming through the choice of distribution function on the space of possibilities. Hence, the mere existence of an ensemble does not by itself support either view. A generating mechanism might spit out numerous copies of one (successful) universe⁴ rather than numerous universes with greatly different properties. Whichever is the case will determine the form of the distribution function [25]. Neither possibility can be excluded without some understanding of the creation mechanism. That mechanism cannot be tested in the true multiverse case and may not be testable in practice even in the multi-domain case. Until it is tested, any specific form assigned to it – in particular, the assumption that it creates generality rather than speciality – is metaphysical rather than physical.

This underlines the point that the present philosophical predilection for generality does not necessarily reflect the nature of physical reality. Indeed, philosophical predilection in cosmology has oscillated from assuming the universe is very special (in the sense postulated by the Cosmological Principle [26, 27]) to assuming that it has attained its present nature through operation of standard physics on generic initial conditions [28, 29]. The present tendency to assume that only the latter assumption is allowed is a philosophical supposition rather than a physical requirement. Either assumption may be allowed by appropriate assumptions about the pre-physics that leads to universe generation.

22.3.4 *Problems with infinity*

It is often claimed that really existing ensembles involve an infinity of universes. However, Hilbert strongly argues that a really existing infinite set is impossible [30]. He points out that the actual existence of the infinite directly or indirectly leads to well recognized unresolvable contradictions in set theory (e.g. the Russell paradox, involving the set of all sets which do not contain themselves) and thus in the definitions and deductive foundations

³ Note that inflation only changes this speciality requirement to some degree; it does not work for very inhomogeneous or anisotropic conditions and, in any case, a general ensemble will have both inflationary and non-inflationary universes.

⁴ For example, $f(m) = 10^{100}\delta(m - m_0)$, where m_0 is the universe domain we inhabit.

of mathematics itself. Hilbert's basic position is that 'the infinite is nowhere to be found in reality, no matter what experiences, observations and knowledge are appealed to'. One can apply this to both individual universes and multiverses. If we assume 'all that can happen does happen', then we run into uncountable infinities of actually existing universes, even in the FLRW case. For example, we have to include all values of the matter and radiation density parameters at a given value of the Hubble parameter, as well as all positive and negative values of the cosmological constant – a triply uncountable set of models. Hilbert would urge us to avoid such catastrophes.

Thus it is important to recognize that infinity is not an actual number which we can ever specify or determine – it is simply the code-word for 'it continues without end'. And something that is not specifiable or determinate in extent is not physically realizable. Whenever infinities emerge in physics, we can be reasonably sure there has been a breakdown in our model. It is plausible that this applies here too.

In addition to these mathematically based considerations, there are philosophical problems with spatial infinities [31], as well as physical arguments against the existence of an infinity in cosmological models. On the one hand, quantum theoretical considerations suggest that spacetime may be discrete at the Planck scale; indeed, some specific quantum gravity models have been shown to incorporate this feature. Not only would this remove the real line as a physics construct, but it could even remove the ultraviolet divergences that otherwise plague field theory – a major bonus. On the other hand, there are problems with putting boundary conditions for physical theories at infinity, and it was for this reason that Einstein preferred to consider cosmological models with compact spatial sections (thus removing the occurrence of spatial infinity). This was a major motivation for his static model, proposed in 1917, which necessarily has compact space sections. Wheeler picked up on this theme and wrote about it extensively [32]. Consequently, the famed textbook *Gravitation* by Misner, Thorne and Wheeler [33] only considered spatially compact, positively curved cosmological models in the main text – those with flat and negative spatial curvatures were relegated to a subsection on 'Other models'.

This theme recurs in present speculations on higher-dimensional theories, where the further dimensions are often (as in the original Kaluza–Klein picture) assumed to be compact. Unless one has some good physical reason for supposing otherwise, one might also expect this to be true of the three dimensions that expanded to a large size, even though this may necessitate 'non-standard' topologies for these spatial sections. Such topologies are

commonplace (indeed they are essential) in M-theory. Thus physics also supports the idea that our universe may have compact spatial sections, which avoids infrared divergences as well.

22.3.5 The existence of regularities

Why is there a uniform structure across all universes m in M ? Any consistent description of M (e.g. through a prescribed set of parameters P) demands regularities across all its members. But that means the existence of similarities which have a common causal source – a generating mechanism of some kind. Such a mechanism is implied in scenarios such as chaotic inflation, where the ensemble consists of domains that are connected to each other in the past, even though they would be causally disjoint in a non-inflationary model. In this case, the existence of such similarities is not mysterious because all members of the ensemble arise from a common origin through a prescribed generating mechanism.

Consider now a genuine multiverse, where the universes are completely disconnected from each other. Why should there be any regularity at all in the properties of these universes? If there are such regularities and specific resulting properties, this suggests that a mechanism created that family of universes and that a causal link to a higher domain was the source of processes leading to these regularities. This, in turn, means that the individual universes making up the ensemble are not actually independent of each other but just products of a single process, or meta-process, as in the case of chaotic inflation. A common generating mechanism is clearly a causal connection, even if not situated in a single connected spacetime, and some such mechanism is needed if all the universes in an ensemble are to have the same properties, for example being governed by the same physical laws or meta-laws.

As emphasized when we considered the description of ensembles, any multiverse with regular properties that we can characterize systematically is necessarily of this kind. If it did not have regularities of properties across the class of universes included in the ensemble, we could not even describe it, much less calculate any properties or characterize a distribution function.

Thus, in the end, the idea of a completely disconnected multiverse – with regular properties but no common causal mechanism – is not viable. Some pre-realization causal mechanism must necessarily determine the properties of the universes in the ensemble. What are claimed to be totally disjoint universes must in some sense be causally connected, albeit in some pre-physical or meta-physical domain.

22.3.6 Hypothesized mechanisms

Many researchers have invoked processes at or near the Planck era to generate a really existing ensemble of expanding domains, one of which is our own. The earliest explicit proposal of this kind was by Vilenkin [1], and Linde's chaotic inflationary proposal [2, 3, 34] is another well known example. The scalar field (inflaton) in these scenarios drives inflation and leads to the generation of a large number of causally disconnected regions. Our own observable region is then situated in a much larger universe that is inhomogeneous on the largest scales. No FLRW approximation is possible globally; rather there are many FLRW-like domains with different FLRW parameters in a single fractal universe [35].

In a stochastic approach [1, 36, 37], probability distributions can be derived for such models from specified inflaton potentials by using the slow-roll approximation. This kind of scenario suggests how overarching physics – or a *law of laws* represented by the inflaton field and its potential, together with the Friedmann and Klein–Gordon equations – can lead to a really existing ensemble of many different FLRW-like regions of a larger universe. Some versions relate this to the huge numbers of vacua of string theory [14, 38]. However, these proposals rely on extrapolations of presently known physics to realms far beyond where its reliability is assured. They also employ inflaton potentials which as yet have no connection to known low-energy particle physics. Nor are these proposals directly testable, since we have no astronomical evidence that the other FLRW-like regions exist. There also remains the problem of infinities, which we discussed above: the continual reproduction of different inflating regions in eternal inflation is claimed to lead to an infinite number of domains. In this case, the supposed infinity of really existent FLRW-like domains derives from the assumed initial infinite (flat or open) space sections, and we have already pointed out the problems in assuming that such space sections are actually realized.

The various physical proposals made for generating mechanisms are either based on unproven physics acting in an existent universe or conceived as mechanisms that precede the existence of physics (since they precede the existence of the universe). In either case, the question raised above recurs in a new form: Why *that* physics and why *this* specific distribution function?

22.4 Problems with proof

The issue of testability underlies the question of whether multiverse proposals are really scientific. There are observational barriers preventing direct proof of the existence of any expanding domains other than the one we live in.

Furthermore, the supposed underlying physics is untested and may always be untestable. Consequently, ensemble proposals are not scientific in the usual sense. In order to make them so – e.g. by showing they are based on a theory that has gained credibility by unifying or clarifying some other mysteries – one has to search for extended ways of relating them to observations.

In looking at these issues, what faces us is not just showing that a multiverse exists. If this is a scientific proposition, one should be able to show what *specific* kind of ensemble is involved, and we have seen there are many different kinds. If you cannot show which *particular* one exists, it is doubtful you can show that any exists at all. If you cannot describe the characteristics of a purported object, then what scientific content can this claim have?

22.4.1 Evidence from observations: true multiverses

There can be no direct evidence for the existence of other universes in a true multiverse, as there is no possibility of even an indirect causal connection. The universes are completely disjoint and nothing that happens in one can affect what happens in another. Since there can be no direct or indirect evidence for such systems, what weight does the claim for their existence carry?

Experimental or observational testing requires some kind of causal connection between an object and an experimental apparatus, so that some characteristic of the object affects the output of the apparatus. But in a true multiverse, this is not possible. No scientific apparatus in one universe can be affected in any way by any object in another universe. The implication is that the supposed existence of true multiverses can only be a metaphysical assumption. It cannot be a part of science, because science involves experimental or observational tests to enable correction of wrong theories. However, no such tests are possible here because there is no relevant causal link.

Now, there is nothing wrong with metaphysical argument when it is appropriate. In this context, it involves a well argued case, based on a generalization of tested physical principles, to produce a conclusion that cannot be tested by any observation whatsoever. However, it must not be confused with science proper, and the claim that the existence of unconnected multiverses is scientifically testable cannot be supported within the usually understood concept of science. A belief that is justified by faith, unsupported by direct or indirect evidence, should be clearly identified as such, so that one knows precisely what one is being asked to support. I suggest the claim that properly disjoint multiverses exist is a metaphysical one, which, by its very nature, can never become a scientific one.

In any case, we have already commented that the idea of completely disconnected multiverses is vitiated by the need to have a common description of the properties of the members of a multiverse. The existence of such a commonality, describable by mathematical relations, must imply some reason for its existence. This presumably comes because the universes were all produced by a common mechanism pre-existing the universes and governing all of them.⁵ So they are not causally unrelated after all, even though the relevant causal mechanism preceded the universes. In order to remain within the domain of science, it seems reasonable to restrict consideration of universe ensembles to multi-domain ensembles rather than multiverses proper (without any common causal mechanism), because the latter cannot even be described, much less shown in any scientific sense to have specific properties. I propose that they should be excluded from the scientific debate.

22.4.2 Evidence and physics: multi-domain universes

In the case of multi-domain universes, there is no direct evidence for the other regions in the ensemble. Nor can there be, since they lie beyond the visual horizon. We will never (on a realistic timescale) receive any information from them. Most are even beyond the particle horizon, so there is no causal connection with them. Nevertheless, they are the result of a common causal mechanism, whether that occurred in a single universe or in some meta-space before the universe came into existence. Thus, one way to make a reasonable claim for existence of a multiverse would be to show that its existence was a more or less inevitable consequence of well established physical laws and processes.

This is essentially the claim made for chaotic inflation. However, as pointed out above, the problem is that the proposed underlying physics has not been tested and may indeed be untestable. There is no evidence that the postulated physics is true, even in our universe, much less in some pre-existing meta-space that might generate an ensemble of universes. The issue is not just that the inflaton is unidentified and its potential untested – it is that we are assuming quantum field theory remains valid far beyond the domain where it has been tested. Can we have faith in that extreme extrapolation, despite all the unsolved problems related to the foundations of quantum theory, the divergences of quantum field theory and the failure of that theory to provide a satisfactory resolution of the cosmological constant problem?

⁵ One might claim that the one multiverse proposal free from this objection is Tegmark's extreme version of all that can happen does happen [8, 15]; but this suffers from major problems to do with infinity and we cannot even describe this possibility, let alone prove it occurs. Claiming existence of something you cannot even properly characterize has dubious scientific merit.

There are two requirements which must be met for a potentially viable ensemble theory. The first is to provide some credible link between presently known physics and the proposed physics underlying the ensemble – a vast extrapolation. The second is to provide at least indirect evidence that the proposed scalar potentials – or some other overarching cosmic principles – really were functioning in the very early universe. Neither requirement has yet been satisfied by any multi-domain proposal. Despite these problems, several arguments have been provided to suggest that we can indeed verify the multiverse proposal and we now discuss these.

22.4.3 *The slippery slope argument*

One argument, due to Rees [12, 13], encourages us to go down the following slippery slope. First, we believe on good grounds that galaxies exist within the visual horizon but beyond the detection limits of current telescopes. We have not seen them yet, but will do so as detectors improve. Second, nobody seriously doubts that galaxies exist in other similar domains that intersect with ours; we share some galaxies with them, even though we do not see the same ones. We believe conditions there are similar to here and have some evidence that this is the case because we can see part of those domains. Third, by a further extension of this argument, it is reasonable to expect that there exist never-observable regions, with no observational connection to our own big bang domain, but with a joint causal past (as in chaotic inflation). Finally, it is reasonable to take another step and assume galaxies exist even in completely disjoint universes – with no causal connection with ours whatsoever. At each step we can reasonably assume that galaxies will continue to exist, because it is just like the previous step.

The problem is that the later steps assume a continuity of structure for which there is no evidence and whose existence would surely rely on a particular kind of common causal mechanism. But there is no guarantee of such continuity at either the last step (the transition to the multiverse) or the preceding one (the transition to a multi-domain universe).⁶ To illustrate this, one could use exactly the same argument to re-assert what used to be taken for granted [26, 27]: that the universe has a *global* Robertson–Walker metric, with spatial homogeneity and isotropy continuing without bound in all directions. But that argument would disprove chaotic inflation, another multiverse contender. Despite this, the proposals are neither provable nor disprovable, because no evidence is available.

⁶ A discussion of testability in this context is given in ref. [39].

22.4.4 The speciality argument

Another argument is based on anthropic considerations and involves the issue of whether our universe is more finely tuned than our presence requires or merely typical of the subset in which we could have emerged. In the first case, the existence of a multiverse to explain such ‘over-tuning’ would be refuted, so the idea would be a scientific one.

The main application of this argument so far has been to the cosmological constant Λ . This is a two-stage argument and one version goes as follows [13]. First, naïve quantum physics implies that Λ should be very large. But our presence requires it to be small enough for galaxies and stars to form; Λ must therefore be below this galaxy-forming threshold. This explains the observed low value of Λ as a selection effect in a really existing ensemble of universes. The probability of a universe with small Λ being selected at random from the set of all universes in the ensemble is very small, but, when we add the prior that life exists, it becomes large. In this way, one justifies the existence of a biophilic universe, even though its *a priori* probability is extremely small. On the other hand, we would not expect any universe that allows life to be more fine-tuned than necessary. Present data indicates that Λ is not much below the threshold value, so our universe is not markedly more special than it needs to be as far as Λ is concerned. Consequently, explaining its fine-tuning by assuming a multiverse is acceptable and suggests that the same argument can be applied to other parameters

Is this argument compelling? As Hartle [40] has pointed out, for the first stage to be useful, we need an *a priori* distribution $f(\Lambda)$ for Λ that is very broad, combined with a very narrow set of values that allow life, these being centred well away from the most probable *a priori* values for Λ . This is indeed the case if we suppose that Λ is centred at a very large value Λ_{prob} (as suggested by field theory) but with a long tail to smaller values, and that $p_{\text{life}}(\Lambda)$ is centred at zero and has a very narrow distribution, as implied by astrophysics. Because the biophilic range with $p_{\text{life}}(\Lambda) > 0$ is so narrow, the function $f_{\text{cc}}(\Lambda)$ will not vary much in this range, so it is equally likely to take any value there. Thus a uniform probability assumption should be reasonably well satisfied within the biophilic range of Λ . Furthermore, this result does not depend critically on a Gaussian assumption for either distribution function – it would be true quite generally [11].

As regards the second stage of the argument, because of the uniform probability assumption, there is an equal *a priori* probability of any value for Λ within the biophilic range, so it is not clear why the expected values for existence of galaxies should pile up near the anthropic limit. Indeed, one

might expect the probability of galaxy formation to be maximal at the *centre* of the biophilic range; the probability drops to zero at the edges because it vanishes outside. In any case, the probabilities are non-zero throughout the biophilic range, so this gives no justification for ruling out a multiverse with any specific value for Λ there.

An alternative form of the analysis uses more detailed calculations of structure formation. This is based on the ‘Principle of Mediocrity’, the assumption that our civilization is typical in the ensemble of all civilizations in our universe [41, 42]. The key equation used is $dP(\rho_V) = P_*(\rho_V)N(\rho_V)d\rho_V$, where $dP(\rho_V)$ is the probability that intelligent life will occur for a vacuum energy density (i.e. an effective cosmological constant) between ρ_V and $\rho_V + d\rho_V$, $P_*(\rho_V)d\rho_V$ is the *a priori* probability that the vacuum energy density will be in this range, and $N(\rho_V)$ is the fraction of baryons that end up in galaxies (it being assumed that life is then guaranteed). The uniform probability assumption implies that $P_*(\rho_V)$ is nearly constant in the range where $N(\rho_V)$ is non-zero. Martel and colleagues [43] calculated $N(\rho_V)$ and showed that – under a specific set of physical assumptions – 5% to 12% of universes would have cosmological constants smaller than our own. This was stated to be a reasonable level of expectation, so the multiverse assumption is not disproved in this case.

But suppose another reasonable set of physical assumptions leads to 0.01% or 0.0001%, as may happen, for example, if we allow other parameters to vary together with Λ [44]. Should we then reject those assumptions? In a context where we already know extreme improbabilities are involved, we can choose this threshold according to taste; the whole point of the argument is to justify a value of $P_*(\rho_V)$ that is different by 120 orders of magnitude from its maximum value. Furthermore, the mediocrity assumption may or may not be true; its adoption is merely a philosophical presupposition. The physical assumptions used in the specific calculation may be reasonable, but they are not scientifically proven.

In the end, there is no way to avoid philosophical decisions, and these shape the outcome of the enquiry. The probabilistic argument is not decisive, because no impossibility is involved. It may give one grounds for saying an ensemble is not unlikely, given the assumptions made, but that is a far cry from proving that it exists.

22.4.5 *The set of possibilities*

Turning to the prior question of what determines the space of all possible universes from which a really existing universe or ensemble of domains is

drawn (Issue 1 in Section 22.2.1), we find ourselves in even more uncertain waters. Suppose we demand some basic meta-principle which delimits the set of possibilities and so ultimately characterizes all the regularities in this possibility space (e.g. that they all obey the principles of quantum field theory). Where would such a principle originate? How can we possibly test its validity for all possible universes? We simply do not have enough theoretical knowledge to describe and delimit reliably the realm of what is possible, and it is unclear how this situation could ever change. Much less do we have any possibility of scientifically testing the nature of this domain. Any assumptions we make about it will necessarily be made on philosophical grounds. However well justified these may be, other possibilities will remain open. Lacking any observational or experimental restrictions, the theory can take any form we like and may be used to justify any conclusion.

22.4.6 Testability: refutation

Despite the gloomy prognosis given above, there are some specific cases where the existence of a multi-domain scenario *can* be disproved. These are when we live in a ‘small universe’, where we have already seen all the way around it [45, 46]. In this case, the universe closes up on itself in a single FLRW-like domain, so there can be no further domains that are causally connected to us.

This proposal is observationally testable; indeed it has been suggested that the power spectrum of the microwave background fluctuations (in particular, the lack of power on the largest angular scales) might already support it [47]. The proposal can be further tested by looking for identical circles in the microwave sky or for an alignment of the quadrupole and octopole axes. (A preliminary identification of the first effect has been made by Roukema and colleagues [48]), and evidence for the second effect is also good according to Katz and Weeks [49]). Confirmation of the small universe hypothesis would disprove the usual multi-domain chaotic inflation scenario but not a true multiverse proposal, since that cannot be observationally falsified or verified.

22.5 Explanatory usefulness and existence

We have seen that there are major problems in confirming any ensemble proposal in the usual scientific manner. We can also ask whether the idea is useful. It does provide a plausible kind of explanation of anthropic coincidences (e.g. in the context of the cosmological constant), but ultimately its usefulness as a scientific proposal is dubious. Also any ensemble proposal

is not a final explanation; it just pushes the ultimate question back one stage further. For if one assumes the existence of a multiverse, the deeper issue then becomes: Why this multiverse rather than another one? Why an ensemble that allows life rather than one that does not [14]? The only multiverse proposal that *necessarily* admits life is Tegmark's extreme version of 'all that can happen does happen' [8]. But then why should this be the one that exists, with its extraordinary profligacy of infinities? The crucial existential questions recur and the multiverse proposal *per se* cannot answer them.

Given its essentially philosophical nature, a useful question is whether there is a philosophically preferable version of the multiverse proposal. In my view, Smolin's idea of a Darwinian evolutionary process in cosmology [9] is the most radical and satisfactory one, because it introduces the crucial idea of natural selection – the one process that can produce apparent design out of mechanistic interactions – into cosmology. Thus it extends fundamental physics to include central biological principles, making it a much more inclusive view than any of the other proposals, which are all based purely on theoretical physics. However, this proposal is incomplete in several ways [50], so it would be helpful to have its physical basis investigated in more detail.

So finally the question is: Does a multiverse in fact exist? The considerations of this article suggest that, in scientific terms, we simply do not know and probably never will. In the end, belief in a multiverse will always be a matter of faith that the logical arguments proposed give the correct answer in a situation where direct observational proof is unattainable and the supposed underlying physics is untestable.

This situation would change if we were able to point to compelling reasons, based on scientific evidence, for a particular specifiable ensemble, or at least a narrowly defined class of ensembles. One way in which this could be accomplished would be by accumulating evidence that an inflaton potential, capable of generating a particular ensemble of domains, was dominant in the very early universe. Otherwise, there will be no way of ever knowing which (if any) particular ensemble is realized. We can always claim whatever we wish about an ensemble, provided it includes at least one universe that admits life. It may contain only one universe or a vast number of them (but not an infinite number if the above arguments are correct) and the evidence will not allow us to choose. Gardner [51] puts it this way:

There is not the slightest shred of reliable evidence that there is any universe other than the one we are in. No multiverse theory has so far provided a prediction that can be tested. As far as we can tell, universes are not even as plentiful as two blackberries.

The existence of multiverses is neither established nor scientifically establishable. The concept is justified by philosophy rather than science. They have explanatory power, but the philosophical nature of their justification must be appreciated.

Acknowledgements

I thank Bill Stoeger and Uli Kirchner for their comments.

References

- [1] A. Vilenkin. The birth of inflationary universes. *Phys. Rev. D* **27** (1983), 2848.
- [2] A. D. Linde. Chaotic inflation. *Phys. Lett.* **B129** (1983), 177.
- [3] A. D. Linde. *Particle Physics and Inflationary Cosmology* (Chur: Harwood Academic Publishers, 1990).
- [4] D. W. Sciama. Is the universe unique? In *Die Kosmologie der Gegenwart*, eds. G. Borner and J. Ehlers (Munich: Serie Piper, 1993).
- [5] J. Leslie. *Universes* (London: Routledge, 1996).
- [6] D. Deutsch. *The Fabric of Reality. The Science of Parallel Universes* (London: Penguin 1997).
- [7] M. Tegmark. Is the Theory of Everything merely the ultimate ensemble theory? *Ann. Phys.* **270** (1998), 1.
- [8] M. Tegmark. Parallel universes. In *Science and Ultimate Reality*, eds. J. D. Barrow, P. C. W. Davies and C. L. Harper (Cambridge: Cambridge University Press, 2004) p. 459.
- [9] L. Smolin. *The Life of the Cosmos* (Oxford: Oxford University Press, 1997).
- [10] D. K. Lewis. *On the Plurality of Worlds* (Oxford: Blackwell, 2000).
- [11] S. W. Weinberg. The cosmological constant problems. In *Sources and Detection of Dark Matter and Dark Energy in the Universe*, ed. D. Cline (Berlin, New York: Springer-Verlag, 2001) [astro-ph/0005265].
- [12] M. J. Rees. *Our Cosmic Habitat* (Princeton: Princeton University Press, 2001).
- [13] M. J. Rees. Numerical coincidences and ‘tuning’ in cosmology. In *Fred Hoyle’s Universe*, eds. C. Wickramasinghe, G. R. Burbidge and J. V. Narlikar (Dordrecht: Kluwer, 2003), p. 95.
- [14] P. C. W. Davies. Multiverse cosmological models. *Mod. Phys. Lett.*, **A19** (2004), 727.
- [15] M. Tegmark. Parallel universes. *Sci. Am.* **288**(5) (2003), 41.
- [16] J. D. Barrow and F. J. Tipler. *The Anthropic Cosmological Principle* (Oxford: Oxford University Press, 1986).
- [17] Y. Y. Balashov. Resource Letter AP-1. The Anthropic Principle. *Am. J. Phys.* **54** (1991), 1069.
- [18] M. J. Rees. *Just Six Numbers, The Deep Forces that Shape the Universe* (London: Weidenfeld and Nicholson, 1999).
- [19] J. D. Bjorken. This volume (2007) [astro-ph/0404233].
- [20] G. F. R. Ellis, U. Kirchner and W. R. Stoeger, Multiverses and physical cosmology. *Mon. Not. Roy. Astron. Soc.* **347** (2003), 921.

- [21] W. R. Stoeger, G. F. R. Ellis and U. Kirchner. Multiverses and cosmology. *Phil. Issues* (2004) [astro-ph/0407329].
- [22] J. Wainwright and G. F. R. Ellis (eds.). *The Dynamical Systems Approach to Cosmology* (Cambridge: Cambridge University Press, 1996).
- [23] G. F. R. Ellis and H. van Elst. Cosmological models. In *Theoretical and Observational Cosmology*, ed. M. Lachieze-Ray (Boston: Kluwer, 1999).
- [24] C. Hogan. Why the universe is just so. *Rev. Mod. Phys.* **72** (2000), 1149.
- [25] U. Kirchner and G. F. R. Ellis. A probability measure for FRW models. *Class. Quant. Grav.* **20** (2003), 1199.
- [26] H. Bondi. *Cosmology* (Cambridge: Cambridge University Press, 1960).
- [27] S. W. Weinberg. *Gravitation and Cosmology* (New York: Wiley, 1972).
- [28] C. W. Misner. The isotropy of the Universe. *Astrophys J.* **151** (1968), 431.
- [29] A. H. Guth. Inflationary universe. A possible solution to the horizon and flatness problems. *Phys. Rev. D* **23** (1981), 347.
- [30] D. Hilbert. On the infinite. In *Philosophy of Mathematics*, eds. P. Benacerraf and H. Putnam (Englewood Cliff, NJ: Prentice Hall, 1964), p. 134.
- [31] G. F. R. Ellis and G. B. Brundrit. Life in the infinite universe. *Quart. J. Roy. Astron. Soc.* **20** (1979), 37.
- [32] J. A. Wheeler. *Einstein's Vision* (Berline: Springer Verlag, 1968).
- [33] C. W. Misner, K. S. Thorne and J. A. Wheeler. *Gravitation* (San Francisco: Freeman, 1973).
- [34] A. D. Linde. Inflation, quantum cosmology and the anthropic principle. In *Science and Ultimate Reality*, eds. J. D. Barrow, P. C. W. Davies and C. L. Harper. (Cambridge: Cambridge University Press, 2003), p. 426.
- [35] A. H. Guth. Eternal inflation. *N.Y. Acad. Sci.* **321** (2001), 66 [astro-ph/0101507].
- [36] A. A. Starobinsky. Current trends in field theory, quantum gravity and strings. In *Lecture Notes in Physics*, **246** (1986), 107.
- [37] A. D. Linde, D. A. Linde and A. Mezhlumian. From the big bang theory to the theory of a stationary universe. *Phys. Rev. D* **49** (1994), 1783.
- [38] L. Susskind. This volume (2007) [hep-th/0302219].
- [39] G. F. R. Ellis. Cosmology and verifiability. *Quart. J. Roy. Astron. Soc.* **16** (1975), 245.
- [40] J. Hartle. This volume (2007) [gr-qc/0406104].
- [41] A. Vilenkin. Predictions from quantum cosmology. *Phys. Rev. Lett.* **74** (1995), 846.
- [42] S. W. Weinberg. *A priori* probability distribution of the cosmological constant. *Phys. Rev. D* **61** (2000), 103505.
- [43] H. Martel, P. Shapiro and S. W. Weinberg. Likely values of the cosmological constant. *Astrophys. J.* **482** (1998), 29.
- [44] M. L. Graesser, S. D. Hsu, A. Jenkins and M. B. Wise. Anthropic distribution for cosmological constant and primordial density perturbations. *Phys. Lett. B* **600** (2004), 15 [hep-th/0407174].
- [45] G. F. R. Ellis and G. Schreiber. Observational and dynamic properties of small universes. *Phys. Lett. A* **115** (1986), 97.
- [46] M. Lachieze-Ray and J. P. Luminet. Cosmic topology. *Phys. Rep.* **254** (1995), 135.
- [47] J. P. Luminet, J. R. Weeks, A. Riazuelo, R. Lehoucq and J. P. Uzan. Dodecahedral space topology as an explanation for weak wide-angle

- temperature correlations in the cosmic microwave background. *Nature*, **425** (2003), 593.
- [48] B. F. Roukema, B. Lew, M. Cechowska, A. Masecki and S. Bajtlik. A hint of Poincaré dodecahedral topology in the WMAP First Year Sky Map. *Astron. Astrophys.* **423** (2004), 821 [astro-ph/0402608].
 - [49] G. Katz and J. Weeks, Polynomial interpretation of multipole vectors. *Phys. Rev. D* **70** (2004), 063527 [astro-ph/0405631].
 - [50] T. Rothman and G. F. R. Ellis. Smolin’s natural selection hypothesis. *Quart. J. Roy. Astron. Soc.* **34** (1992), 201.
 - [51] M. Gardner. *Are Universes Thicker than Blackberries?* (New York: W. W. Norton, 2003).

23

Predictions and tests of multiverse theories

Don N. Page

Institute for Theoretical Physics, University of Alberta

23.1 Multiverse explanations for fine-tuning

Many of the physical parameters of the observed part of the Universe, whether constants of nature or cosmological boundary conditions, seem fine-tuned for life and us [1–4]. There are three common explanations for this. One is that there is a ‘Fine-Tuner’ who providentially selected the physical parameters so that we can be here. Another is that it is just a coincidence that the parameters turned out to have the right values for us to be here. A third is that the observed Universe is only a small part of a much vaster Universe or multiverse or megaverse or holocosm (my own neologism for the whole), and that the physical parameters are not the same everywhere but take values permitting us in our part.

These three explanations are not necessarily mutually exclusive. For example, combining a Fine-Tuner with coincidence but without a multiverse, perhaps the Universe was providentially created by a God who had a preference for a particularly elegant single universe which only coincidentally gave values for the physical parameters that allowed us to exist. Or, for a Fine-Tuner with a multiverse but without coincidences, perhaps God providentially created a multiverse for the purpose of definitely creating us somewhere within it. Or, for coincidence and a multiverse without a Fine-Tuner, if the Universe were not providentially created, it might be a multiverse that has some parts suitable for us just coincidentally. Or, it might even be that all three explanations are mutually true, say if God providentially created a multiverse for reasons other than having us within it, and yet it was a coincidence that this multiverse did contain us.

On the other hand, it seems conceivable (in the sense that I do not see any obvious logical contradiction) that the Universe is determined by some sort of blind necessity that requires both our own existence and a single

world with a single set of physical parameters. In this case, the Universe is not providential (in the sense of being foreseen by any God), but nor is our existence coincidental.

Thus, logically, I do not see that we can prove that any combination of the three explanations is either correct or incorrect. However, it does seem a bit implausible that none of these explanations is at least partially correct, and it also seems rather implausible that the large number of fine-tunings that have been noticed are mere coincidences.

I should perhaps at this point put my metaphysical cards on the table and say that – as an evangelical Christian – I do believe the Universe was providentially created by God, and that – as a quantum cosmologist with a sympathy toward the Everett ‘many worlds’ version of quantum theory – I also strongly suspect that the Universe is a multiverse, with different parts having different values of the physical parameters. It seems plausible to me that – in a quantum theory with no arbitrary collapses of the wave-function – God might prefer an elegant physical theory (perhaps string/M-theory with no adjustable dimensionless parameters) that would lead to a multiverse that nevertheless has been created providentially by God with the purpose of having life and us somewhere within it.

Although personally I have less confidence in string/M-theory than in either providence or the multiverse, nevertheless string/M-theory is very attractive. It does seem to be the best current candidate for a dynamical theory of the Universe (i.e. for its evolution, if not its state), and it does strongly appear to suggest a multiverse. Since string/M-theory has no adjustable dimensionless constants, if it predicted just a single set of parameters, it would seem very surprising if these parameters came out right for our existence. Thus, if string/M-theory – or some alternative with no adjustable dimensionless constants – were correct, it would seem much more plausible that it would lead to a multiverse, with different parts of the Universe having different physical parameters.

Indeed, string theorists [5–15] have argued that string/M-theory leads to an immense multiverse or landscape of different values of physical parameters and ‘constants of nature’. It is not yet known whether the range of values can include the physical parameters that allow life, such as those within our part of the Universe, but that does seem at least plausible with the enormous range suggested in the string landscape or ‘stringscape’.

One objection that is often raised against the multiverse is that it is unobservable. Of course, this depends on how the multiverse is defined. One definition would be the existence of different parts, where some physical parameters are different, but this just shifts the arbitrariness to the choice

of this set of physical parameters. Obviously if some quantity which varies with position (such as energy density) were included in the set of physical parameters, then even what we can see could be considered a multiverse. But if we just include the so-called ‘constants of nature’, such as the fine structure constant and various other coupling constants and the mass ratios of the various elementary particles, then what we can observe directly seems to consist of a single universe. Indeed it would be rather natural – if *ad hoc* – to define a multiverse with respect to the physical parameters that have no observable variation within the part we can directly see. In this case, the multiverse becomes unobservable, and it becomes an open question whether parts of the Universe we cannot see have different values of these constants. Many would argue that it is a purely metaphysical concept that has no place in science.

However, in science we need not restrict our entities to be observable – we just want the simplest theory, whether using observable or unobservable entities, to explain and predict what is observable. One cannot test scientifically a theory that makes predictions about what is unobservable, but one can test a theory that makes use of unobservable entities to explain and predict the observable ones. Therefore, if we find a multiverse theory that is simpler and more explanatory and predictive of what is observed than the best single-universe theory, then the multiverse theory should be preferred. The success of such a multiverse theory itself would then give credence to the existence of the unobservable multiverse.

Another objection that is often raised against multiverse theories is that, naïvely, they can ‘explain’ anything and predict nothing, so that they cannot be tested and considered scientific. The idea is that if a multiverse gives all possible physical parameters or other conditions somewhere within the multiverse, then the parameters and conditions we observe will exist somewhere. Hence what we observe is ‘explained’ at least somewhere. On the other hand, if every possibility exists, then we cannot predict any non-trivial restriction on what might be observed. If a theory makes no non-trivial predictions, then it cannot be tested against observations, and it can hardly be considered scientific.

23.2 Testable multiverse explanations

Sufficiently sophisticated multiverse theories can provide predictions as well as explanations, and hence can be tested against observations scientifically. Unlike single-universe theories, in each of which one can, in principle, predict uniquely the physical parameters, in multiverse theories one usually can

make only statistical predictions for ranges of parameters, but this can still be much better than making no prediction at all. However, to make such statistical predictions, the multiverse theory needs to include a *measure* for the different observations that can be made. If it allows all possible observations without putting any measure on them, then one can make no predictions.

Since we have strong evidence that we live in a quantum universe, it would be natural to seek a quantum multiverse theory. If this just includes some quantum states, unitary evolution, path integrals, operators, some operator algebra and the like, one has the bare quantum theory eloquently described by Sidney Coleman,¹ which by itself does not give any measures or probabilities. The Copenhagen version of quantum theory does give these, but at the apparent cost of the collapses of the wave-function at times undetermined by the theory and to states that are random.

Here I shall take essentially an Everett ‘many worlds’ view that, in actuality, there is no collapse of the wave-function. However, to achieve testability of the quantum theory, I shall assume that there is one aspect of the Copenhagen version that should be added to the bare quantum theory: measures for observations that are expectation values of certain corresponding ‘awareness operators’.

In Copenhagen theory, these operators are projection operators, and the measures are the probabilities for the results of the collapse of the wave-function. Here I shall not necessarily require the operators to be projection operators, though – to give the positivity properties of measures – I shall assume they are at least positive operators. Also, I shall not assume that anything really random occurs, such as wave-function collapse, but that there are simply measures for all the different observations that might occur. In testing the theory against one’s observation, one can regard that observation as being selected at random (with the theory-given measure) from the set of all possible observations, but ontologically one can assume that all possible observations with non-zero measure really do occur, so that there is never a real physical random choice between them.

For the quantum theory to be fundamental, one would need to specify which observations have measures and what the corresponding operators are whose expectation values give those measures. In my opinion, the most fundamental aspect of a true observation is a conscious perception or awareness of the observation. Therefore, I have developed the framework of ‘Sensible Quantum Mechanics’ (SQM) [16] or ‘Mindless Sensationalism’ [17] for

¹ S. Coleman. Quantum mechanics with the gloves off. Dirac Memorial Lecture, St. John’s College, University of Cambridge, June 1993 (unpublished).

giving the measures for sets of conscious perceptions as expectation values of corresponding positive operators that I call ‘awareness operators’. This is only a framework (analogous to the bare quantum theory without the detailed form of the unitary evolution or operator algebra) rather than a detailed theory, since I have no detailed proposal for the sets of possible conscious perceptions or for the corresponding positive operators. Presumably, for human conscious perceptions, these operators are related to states of human brains, so understanding them better would involve brain physics. However, I do not see how they could be deduced purely from an external examination of a brain, since we cannot then know what is being consciously experienced by the brain.

To avoid the complications of brain physics, one might use the observed correlation between external stimuli and conscious experiences to replace the unknown awareness operators acting on brain-states with surrogate operators acting on the correlated external stimuli. Of course, this would not work well for illusory or hallucinatory conscious perceptions, for which the fundamental awareness operators would presumably still work if they were known. However, one might prefer to focus on conscious perceptions that are correlated with external stimuli and hence better fit what is usually meant by observations.

If the awareness operator for a conscious perception is correlated with a single set of external stimuli at a single time, it could be approximately replaced by a single projection operator onto some external system. Alternatively, if it is correlated with a sequence of measurement processes, then it could be approximately replaced by a product of projection operators or a sum of such products, a class operator of the decoherent histories approach to quantum theory [18–20].

Therefore, though I would not regard either the projection operators of Copenhagen quantum theory or the class operators of decoherent histories quantum theory as truly fundamental in the same way that I believe awareness operators are, it might be true that, in certain circumstances, these are reasonable approximations to the fundamental awareness operators. Then one can take their expectation values in the quantum state of the Universe as giving the measure for the corresponding conscious perception.

One example of this replacement would be to calculate the measure for conscious perceptions of a certain value of the Hubble constant. In principle, in SQM this would be the expectation value of a certain awareness operator that presumably acts on suitable brain-states in which the observer is consciously aware of that particular Hubble constant value. But the expectation value of this operator might also be well approximated by that of some

suitable operator acting on the logarithm of the expansion rate of the part of the Universe that is observed. Because the latter operator does not involve brain physics, it might be easier to study scientifically and so could be used as a good surrogate for the actual awareness operator.

However, it would presumably not be a good approximation to use the latter operator if its expectation value depended significantly on parts of the Universe where there are no conscious observers; if one wants to use it to mimic the expectation value for the perceptions of conscious observations, one must include a selection effect which restricts the operator to parts of the Universe where there are conscious observers.

To include this selection effect in operators that are external to brains (or whatever directly has the conscious perceptions), so that their expectation values can be good approximations for those of the fundamental awareness operators, is a difficult task, since we do not know the physical requirements for conscious observers. For example, there is nothing within our current understanding of physics that would tell us whether or not some powerful computer is conscious, unless one makes assumptions about what is necessary for consciousness. Also, I know of nothing within our current understanding of physics that would enable us to predict that I am currently conscious of some of my visual sensations but not of my heartbeat, since presumably information about both is being processed by my brain and would be incorporated in a purely physical analysis.

Nevertheless, to formulate a very crude guess for a selection effect for conscious observers, one might make the untested hypothesis that typical observers are like us in requiring suitable complex chemical reactions and perhaps a liquid compound like water. Then one could use the existence of liquid water as a very crude selection effect for observers and attach it onto other projection or class operators used to approximate some conscious perception depending on the external stimuli that are described by the projection or class operators.

Thus one might use projection or class operators to ask the following two questions. Does liquid water exist in part of the Universe? Is that part of the Universe expanding at a suitable logarithmic rate? If the answer to these questions is yes with some measure, then one might expect that there would be a roughly corresponding expectation value for the awareness operator for conscious perceptions of that value of the Hubble constant. This is an extremely crude approximation to what I postulate would objectively exist as the expectation value of the true corresponding awareness operator, but since these awareness operators are, as yet, largely unknown, the crude approximation may be useful during our present ignorance.

One problem with calculating the measure for sets of conscious perceptions as expectation values of corresponding ‘awareness operators’ is that, naïvely, one might get infinite values. By itself this would not necessarily be a problem, since only ratios of measures are testable as conditional probabilities. However, when the measures themselves are infinite, it is usually ambiguous how to take their ratios.

The problem arises if the awareness operators are sums of positive operators that are each localized within finite spacetime regions (as one would expect if the operators correspond to finite conscious beings). Assume that one such operator in the sum has support within one of N spacetime regions of equal volume within the total spacetime. Then, by translational or diffeomorphism invariance, one would expect the sum of the operators for a particular awareness operator to include a sum over the corresponding operators in each of the N regions. (There would also be a sum over operators that overlap different regions, but we need not consider those for this argument.) This is essentially just the assumption that, if a suitable brain-state for some conscious perception can occur in one of the N spacetime regions, then it can also occur (depending on the quantum state) in any of the other $N - 1$ regions. Also, where it occurs in some coordinate system should not affect the content of the conscious perception produced by the corresponding brain-state.

If the conditions for observers with the corresponding conscious perception occur within all N spacetime regions, so that the expectation value of the operator within each region has a positive expectation value bounded from below by a positive number ϵ , then the total awareness operator (a sum of at least the individual positive operators within each of the N regions) will have an expectation value at least as large as $N\epsilon$. This is infinite if the number N of such spacetime regions is infinite. Essentially the argument is that, if the measure for a conscious perception has a strictly positive (but finite) expectation value for each spacetime volume in some region, then for an infinite volume of spacetime where this is true the measure will be infinite. One can regard this as arising from the infinite number of conscious observers that arise in an infinite volume of spacetime with conditions suitable for life and conscious observers.

Since inflation tends to produce a universe that is arbitrarily large (with an infinitely large expectation value for the spatial volume at any fixed time after inflation and hence presumably infinitely many conscious observers), it tends to produce an infinite measure for almost all non-zero sets of conscious observations. There has been a lot of discussion in the literature [21–27] of how to obtain well defined ratios of these infinite measures (or of related

quantities, since the discussion is not usually in terms of measures for conscious perceptions), but I think it is fair to say that there is as yet no universally accepted solution.

This is a serious problem that needs to be solved before we can hope to make rigorous testable predictions for an inflationary multiverse. A vague hope is that somehow the dimensionality of the part of the Hilbert space (or quantum state space if it is bigger than the Hilbert space) where conscious observers are supported is finite, so that – for all finite quantum states – the expectation values of all finite positive operators (including the awareness operators) would be finite, thus giving finite measures for all conscious perceptions. But what would limit conscious observers to a finite-dimensional part of the presumably infinite-dimensional quantum state space eludes me.

23.3 Testing multi-observation theories with typicality

If we can find a theory that gives finite measures for sets of observations (perhaps conscious perceptions) or which can be approximated as the expectation values of other positive operators, how can we test it? If the theory predicts a unique observation (at least unique under some condition, such as observing a clock reading to have some value), then one can simply check whether one's observation fits the prediction. This would typically be the case in a classical model of a universe with a single observer who reads a clock that gives monotonically increasing readings (so that there is only a single observation for each clock reading).

Although a classical solipsist might believe this is true for his universe, for most of us the evidence is compelling that there are many observers and hence presumably many different observations even at one value of some classical time. Quantum theory further suggests that there are many possible observations – even for a single observer at a single time.

There is a debate as to whether the observations given by quantum theory are actual or are merely unrealized possibilities. The Copenhagen view seems to imply that – for each value of the time and for each observer – there is only one observation that is actualized (say by collapse of the wave-function), so that all the other possibilities are unrealized. This seems to come from a naïvely WYSIWYG² view of the Universe, so to me it is much simpler to suppose that all possible observations predicted by the quantum theory are actualized, with no ugly collapse of the wave-function to give a single actualized observation for each observer at each time. We are already

² What you see is what you get.

used to the idea of many different times (which are effectively just different branches of the quantum state, at least in the Wheeler–DeWitt approach to quantum gravity) and – except for solipsists – to the idea of many different observers, so why should we not accept the simple prediction from quantum theory of many observations at the same time by the same observer?

In any case, whether in a classical universe or a quantum universe without collapse of the wave-function, each time an observation occurs, there are many observations even at the same time, and so one needs to be able to test this. To do this for a theory that gives measures for all sets of observations, I would propose using the concept of ‘typicality’ [16], which is a suitable likelihood that one may use to test or compare theories or to calculate their posterior probabilities in a Bayesian analysis after assigning their prior probabilities.

The basic idea is to choose a set of possible observations that each give a single real parameter, such as the Hubble constant or the value of one of the constants of nature. Then we use the measure for sets of observations to get the measure for all ranges of this single real parameter. For simplicity, we normalize the total measure in the set of observations being considered to be unity.

Now we want to test our observation against the theory by calculating the typicality for that observation within the set. For simplicity, I shall call the observation being tested the ‘actual’ observation, even though the theory would say that all possible observations with non-zero measure are realized as actual observations. To do this, one calculates the total ‘left’ and ‘right’ measures for all possible observations in the set under consideration, i.e. the total measure to the left or right of and including the ‘actual’ observation when they are ordered on the x -axis by the value of the real parameter under consideration. These two measures will add up to unity plus the measure of the ‘actual’ observation, which is counted in both of the measures.

Next take the smaller of these two measures (if the ‘actual’ observation is not in the middle of the total measure) as the ‘extreme’ measure of the ‘actual’ observation. We then use the normalized measure of the set of observations to calculate the probability that a random observation within the set would give an ‘extreme’ measure as small as that of the ‘actual’ observation. This probability is what I call the ‘typicality’ of the actual observation of the real parameter within the chosen set of possible observations. The typicality is thus the probability that a random observation in the set is at least as extreme as the actual observation. It depends not only on the actual observation, but also on the theory predicting the measure for the sets of

observations. This is what is needed to calculate the conditional probability of subsets of observations within the set under consideration.

In the case in which the real parameter takes a continuum of values and there is zero measure for an observation to have precisely any particular value, the left plus right measures add up to unity. Then the extreme measure (the smaller of the left and right measures) will take continuous values from zero to one-half with a uniform probability distribution, so the typicality is twice the extreme measure. In this simple case, the typicality is a random variable with a uniform probability distribution ranging from zero (if the actual parameter is at the extreme left or right) to unity (if the actual value is in the middle of its measure-weighted range, with both left and right measures being one-half).

If the real parameter takes on discrete values, then the situation is more complicated. For example, suppose that the real parameter is k , with possible values $k = -1$ (with measure 0.2), $k = 0$ (with measure 0.35) and $k = +1$ (with measure 0.45). Then $k = -1$ has a left measure of 0.2 and a right measure of $0.2 + 0.35 + 0.45 = 1$ for an extreme measure of 0.2; $k = 0$ has a left measure of $0.2 + 0.35 = 0.55$ and a right measure of $0.35 + 0.45 = 0.8$ for an extreme measure of 0.55; and $k = +1$ has a left measure of $0.2 + 0.35 + 0.45 = 1$ and a right measure of 0.45 for an extreme measure of 0.45. Thus the probability of an extreme measure of 0.2 is 0.2 (the probability of $k = -1$); the probability of an extreme measure of 0.45 is 0.45 (the probability of $k = +1$); and the probability of an extreme measure of 0.55 is 0.35 (the probability of $k = 0$). The typicality of $k = -1$ is the probability that the extreme measure will be at least as small as 0.2, which is 0.2; the typicality of $k = 0$ is the probability that the extreme measure will be at least as small as 0.55, which is $0.2 + 0.45 + 0.35 = 1$, and the typicality of $k = +1$ is the probability that the extreme measure will be at least as small as 0.45, which is $0.2 + 0.45 = 0.65$.

Note that only for the most extreme parameter value or values (for which the extreme measure is the smallest possible within the set) is the typicality the same as the normalized measure of the observation giving that value itself. For less extreme parameter values, the typicality is greater than the measure of the observations giving that parameter value. On the other hand, the least extreme parameter value or values (the middle one, for which the 'extreme' measure is the greatest possible within the set) has a typicality of unity. Thus the typicality always attains its upper limit of unity for some member of the set, but the lowest value it attains is the measure of the most extreme observation (which would be zero if the observed parameter formed a continuum with zero measure for any particular value of the parameter).

The typicality is thus a likelihood, given a theory for the measures of sets of values of a real parameter, for a parameter chosen randomly with the probability measure given by the theory, to be at least as extreme as the ‘actual’ observed parameter. The typicality has the advantage over the probability measure for the actual observed parameter of being a probability that has values up to unity for some possible observation. This differs from the probability measure for the parameter itself, which may have a very small upper limit (e.g. if there is an enormous number of possible discrete values for the parameter) or even a zero upper limit (e.g. if the parameter ranges over a continuum and has a smooth probability density, with no delta functions at any particular values of the parameters).

If one uses the probability measure itself as a likelihood, one cannot directly perform a Bayesian analysis with an observation of a continuous parameter having a smooth probability density, since the resulting likelihood will be zero for all possible observed values of the parameter. One might try to use the probability density instead of the probability itself, but this depends on the coordinatization of the parameter and so gives ambiguous results. For example, one would get a different likelihood for an observed value of the Hubble constant H by using its probability density than one would for H^2 .

Another approach that is often used for results that have a large number of possible values is to bin them and then use the total probability for the bin in which the actual observation lies as the likelihood. But again this depends on the bins and so gives ambiguous results. The ambiguity of both the probability density and the binning are avoided if one uses the typicality as I have defined it here.

Admittedly, if there are $N > 1$ parameters being observed, then there are ambiguities even with the typicalities. First, with more than one parameter, one gets more than one typicality. Second, if there are N independent parameters, one can construct N independent combinations of them in arbitrarily many different ways. Both of these problems are related to the issue of how one chooses to test a theory, which has no unique answer.

Once one has made a choice of what set of observations to include and what parameter to determine the typicality for, how do we use the typicality to test a theory? It can be used – like any other likelihood – in the following manner. Let H_n be an hypothesis that gives measures to observations in the set, so that an actual observation O has typicality $T_n(O)$ according to this hypothesis. At the simplest level, one can say that, if $T_n(O)$ is low, then H_n is ruled out at the corresponding level. For example, if $T_n(O) < 0.01$, then one can say that H_n is ruled out at the 99% confidence level.

A better approach would be to assign initial or prior probabilities $P_i(H_n)$ to different hypotheses H_n , labelled by different values of n . Then the typicalities $T_n(O)$ for these different hypotheses would be used as weights to adjust the $P_i(H_n)$ to final or posterior probabilities $P_f(H_n)$ that are given by Bayes' formula:

$$P_f(H_n) = \frac{T_n(O)P_i(H_n)}{\sum_m T_m(O)P_i(H_m)}. \quad (23.1)$$

Apart from the ambiguity of choosing the set of possible observations and the parameter to be observed, and the physics problem of calculating the typicalities $T_m(O)$ assigned by each theory H_m , there is now the new ambiguity of assigning prior probabilities $P_i(H_m)$ to the theories themselves. This appears to be a purely subjective matter, though – in the spirit of Ockham's razor – scientists would generally assign higher prior probabilities to simpler theories. Of course, there are arbitrarily many ways to do that. However, if one just considered an infinite countable set of theories that one could order in increasing order of complexity, from the simplest H_1 to the next simplest H_2 and so on, then one simple assignment of prior probabilities would be

$$P_i(H_m) = 2^{-m}. \quad (23.2)$$

The idea of restricting attention to a countable set of theories seems plausible, since humans could really consider only a finite set of theories, but it could be inappropriate if the ultimate theory of the Universe contained an infinite amount of information, even if merely in the form of a single real coupling constant or some other parameter whose digits are not compressible (i.e. generated by a finite amount of input information). Note that it is considered to be a merit of string/M-theory that there is not even the possibility of having infinite amounts of information in any dimensionless coupling constants, at least in the dynamical equations of the theory, although it is apparently not yet ruled out that the quantum state might have an infinite amount of information. This might apply to the expectation value of the dilaton, although most theorists would also prefer to avoid this possibility of an infinite amount of information in the dilaton.

23.4 Testing the single-universe and multiverse hypotheses

Tegmark [28–30] has classified multiverse hypotheses into Levels 1, 2, 3 and 4. Level 1 comprises regions beyond our cosmic horizon, with the same 'constants of nature' as our own region. Level 2 describes other post-inflation

bubbles, perhaps with different ‘constants of nature’. Level 3 is the Everett many worlds of quantum theory, with the same features as Level 2. Level 4 includes other mathematical structures, with different fundamental equations of physics as well as different constants of nature.

Levels 1–3 can all come from a single universe if we define a universe to be some quantum state in some quantum state space (e.g. some C^* -algebra state). In this case, the quantum state space may be regarded as a set of quantum operators and their algebra, and the quantum state as an assignment of an expectation value to each quantum operator. To obtain measures for observations in the form of conscious perceptions, one must add to this bare quantum theory an assignment of a particular positive operator for each set of conscious perceptions. The resulting ‘awareness operators’ then form a positive-operator-valued set obeying the appropriate sum rules when one forms unions of disjoint sets of conscious perceptions, so that the resulting expectation values have the properties of a measure on sets of conscious perceptions [16, 17].

Different hypotheses H_m that each specify a single SQM universe would give different quantum state spaces, different operator algebras, different quantum states, different sets of conscious perceptions and/or different sets of awareness operators corresponding to the sets of conscious perceptions. (A quantum state is here defined, in the C^* -algebra sense, as the quantum expectation values for all possible quantum operators in the set.) By the SQM rule that the measure for each set of conscious perceptions is the expectation value given by the quantum state for the corresponding awareness operator, a definite SQM theory H_n would give a definite measure for each set of possible conscious perceptions. This would be a theory of a single SQM universe, though that universe could be a multiverse in the senses of Levels 1–3.

Then, by the procedure outlined above, from one’s actual observation O , a sufficient intelligence should be able to calculate for each H_m the typicality $T_m(O)$ of that observation. If one has a set of such theories with prior probabilities $P_i(H_m)$, then one can use a Bayesian analysis to calculate the posterior probability $P_f(H_n)$ for any specific theory H_n and thereby test the theory at a statistical or probabilistic level.

But what if there is more than one universe? Tegmark [28–31] has raised the possibility of a multiverse containing different mathematical structures, and it certainly seems logically conceivable that reality may consist of more than one universe in the sense of Levels 1–3. Tegmark discusses a Level 4 multiverse which, as he describes it, includes all mathematical structures. This seems to me logically inconsistent and inconceivable. My argument

against Level 4 is that different mathematical structures can be contradictory, and contradictory ones cannot co-exist. For example, one structure could assert that spacetime exists somewhere and another that it does not exist at all. However, these two structures cannot both describe reality.

Now, one could say that different mathematical structures describe different existing universes, so that they each apply to separate parts of reality and cannot be contradictory. But this set of existing universes, and the different mathematical structures with their indexed statements about each of them, then forms a bigger mathematical structure. At the ultimate level, there can be only one world and, if mathematical structures are broad enough to include all possible worlds or at least our own, there must be one unique mathematical structure that describes ultimate reality. So I think it is logical nonsense to talk of Level 4 in the sense of the co-existence of all mathematical structures. However, one might want to consider how to test levels of the multiverse between Levels 1–3 and 4.

One way to extend an SQM universe to a multiverse might be to allow more than one quantum state on the same quantum state space, while keeping the other parts of the structure – such as the awareness operators – the same. Then, if a weight is assigned to each of these different quantum states, one can get the measure for each set of conscious perceptions as the weighted sum of the measures for each quantum state. But this is equivalent to defining a new single quantum state in a new single-universe theory that is the weighted sum of these different quantum states in the original description. That is, the new single quantum state would be defined to give as the expectation value of each operator the weighted sum of the expectation values that the different quantum states would give. (If the quantum state can be described by a density matrix, then the new density matrix would be the weighted sum of the old ones.)

Since the measure for a set of conscious perceptions in an SQM universe is the expectation value given by the quantum state of the awareness operator corresponding to the set of conscious perceptions, one would get the same measure by using the new quantum state as by taking the weighted sum of the measures in the old description in which there are different quantum states.

Another way to get a broader multiverse would be to keep the same quantum state space, quantum operators, operator algebra and set of possible conscious perceptions, but to include different sets of awareness operators in different SQM universes. But again, if one weights the resulting measures for each universe to get a total measure for this multiverse, this would be equivalent to forming a single new set of awareness operators that are each

the weighted sum of the corresponding awareness operators in each of the different universes.

Yet another way to extend the multiverse would be to include universes with separate quantum state spaces, each with its own quantum state and awareness operators. If each of these universes has a weight, then one can again get the total measure for each set of conscious perception by taking the weighted sum of the measure for that set in each universe. This would be equivalent to defining a total quantum state space whose quantum operators were generated by the tensor sum of the operators in each of the original sets of operators that correspond to the original separate quantum state spaces. One could take operators from different original sets as commuting to define the quantum algebra of the new set.

The new single quantum state could then be defined by giving – on any sum of operators from the separate sets of operators – the weighted sum of expectation values that the old quantum states gave. For products of operators from different sets, one could just take the new expectation value to be the product of the weighted old expectation values for the separate operators in each set. The new awareness operators could be defined as the sum of the original awareness operators. Since this would involve only sums from the different sets of operators and not products, the expectation values of the new awareness operators would all be linear in the weights for the original separate universes in the new single quantum state and hence would give in that new single quantum state the same measure as the weighted sum of the original measures.

Each of these three simple-minded ways to attempt to extend the multiverse produces nothing new, at least for the measures of sets of conscious perceptions. Thus a single SQM universe is a fairly broad concept, encompassing a wide variety of ways of generating measures for conscious perceptions. In fact, one could argue that any assignment of measures for conscious perceptions could come from a single SQM universe, since one could just define awareness operators for all sets of conscious perceptions and embed these into a larger set of quantum operators with some algebra. One could then just choose the quantum state to give the desired expectation values for all of the awareness operators.

In principle, one could even choose the algebra of operators to be entirely commuting, so that the resulting quantum theory would be entirely classical, though still possibly giving the Everett many worlds rather than just a single classical world. Thus, even a universe that gives exactly the same measures for conscious perceptions as ours, and hence the same typicalities for all observations, could, in principle, be entirely classical in the sense of being

commutative. We cannot prove that a universe is quantum just from our observations.

However, surely such a classical description of our conscious perceptions would involve a more complicated SQM universe than one in which there are non-commuting operators (and presumably even non-commuting awareness operators). Thus, it is on the grounds of simplicity and Ockham's razor that we assign higher probabilities to non-commuting quantum theories that explain our observations, even though the likelihoods for our observations can be precisely the same in a classical theory. In a similar way it might turn out that, although a multiple-SQM-universe theory could be reduced to a single-SQM-universe theory in one of the ways outlined above, the description could be simpler in terms of the former or even in terms of universes that are not SQM.

If we do have a true multiverse of different universes, each of which gives a measure for each set of conscious perceptions, then to get a measure covering the whole of reality, we would need a measure for each of the individual universes. Suppose each universe is described by an hypothesis H_n that assigns a measure $\mu_n(S)$ for each set S of conscious perceptions. When we were considering single universes, we considered different H_m just as theoretical alternative possibilities and discussed assigning subjective prior probabilities $P_1(H_m)$ to them. But when we are considering true multiverses, we need an objective weight $w(H_n)$ for each universe, since each universe with non-zero weight is being considered as actually existing. Therefore the total measure for each set of conscious perceptions from this extended multiverse would be $\mu(S) = \sum_n w(H_n)\mu_n(S)$.

Extending the multiverse to multiple SQM universes (or to any ensemble in which there is a prediction for the measure for all sets of conscious perceptions from each universe) replaces our uncertainty about which H_n is correct with the uncertainty about which $w(H_n)$ is correct. It would replace Tegmark's question [28–31] 'Why these equations?' with 'Why this measure?' We cannot evade some form of this question by invoking ever higher levels of the multiverse, even though this may provide a simpler description of a world.

In the sense that an SQM universe is a single universe, it may still encompass Level 1–3 multiverses. At the true multiverse level, we need not just a single theory H_n for a single universe, but also a meta-theory I for the measure or weight $w(H_n)$ of the single universes within the set of actually existing multiverses. However, since we do not yet know what the correct meta-theory is, just as we do not yet know what the correct theory H_n is for our single universe, we may wish to consider various theoretically possible

meta-theories, I_M , labelled by some index M in the same way that n labelled the single universe described by the theory H_n . Then meta-theory I_M says that single universes exist with measures $w_{M,n} \equiv w_M(H_n)$ and so a set of conscious perceptions S would have measure $\mu_M(S) = \sum_n w_{M,n} \mu_n(S)$. From the measure for conscious perceptions, one can follow the procedure outlined in Section 23.3 to get the typicality $T_M(O)$ of an observation O in meta-theory I_M .

For example, if the single universes described by H_n are labelled by the positive integers n in order of increasing complexity, and if the meta-theories I_M are labelled by the positive integers M , one might imagine the following choice for the weights $w_{M,n}$ of the meta-theory I_M to give the universe H_n :

$$w_{2m-1,n} = \frac{1}{m} \left(\frac{m}{m+1} \right)^n, \quad w_{2m,n} = \delta_{mn}. \quad (23.3)$$

Then, for odd M , one gets a geometric distribution of weights over all single universes described by the theories H_n , with the mean of n being $m+1$. However, for even M , one gets a non-zero (unit) weight only for the unique single universe described by the theory H_m . Thus the odd members of this countable sequence of meta-theories do indeed give multiverse theories with various weights, but the even members give single-universe theories.

Just as in a Bayesian analysis for single-universe theories we needed subjective prior probabilities $P_1(H_m)$ for the possible single-universe theories H_m , so now for a Bayesian analysis of multiverse meta-theories I_M , we need subjective prior probabilities $P_1(I_M)$. Again, although these subjective prior probabilities are really arbitrary, we may wish to invoke Ockham's razor for the meta-theories and assign the simpler ones the greater prior probabilities. For example, if we can re-order the I_M in increasing order of complexity by another natural number $N(M)$, one might use the simple subjective prior probability assignment:

$$P_1(I_M) = 2^{-N(M)}. \quad (23.4)$$

This would imply that the simplest meta-theory ($N=1$) is assigned 50% prior probability of being correct, the next simplest ($N=2$) 25%, etc.

For a more *ad hoc* choice, one could take the meta-theory weights given by the hybrid model of Eq. (23.3) for both single and multiple universes and arbitrarily set

$$P_1(I_{2m-1}) = P_1(I_{2m}) = 2^{-m-1}. \quad (23.5)$$

This gives a total prior probability of $1/2$ for single-universe (even M) theories and $1/2$ for multiple-universe (odd M) theories. This might be viewed as a compromise assignment if one is *a priori* ambivalent about whether a single-universe or multiple-universe theory should be used.

23.5 Conclusions

Even though multiverse theories usually involve unobservable elements, they may give testable predictions for observable elements if they include a well defined measure for observations. One can then analyze them by Bayesian means, using the theory-dependent typicality of the result of observations as a likelihood for the theory, though there is still an inherent ambiguity in assigning prior probabilities to the theories.

One can try to avoid specifying the equations or other properties of an individual universe by assuming that there is an ensemble of different universes, but this replaces the question of the equations with the question of the measure for the different universes in the ensemble. There is no apparent way to avoid having non-trivial content in a testable theory fully describing all of reality.

Acknowledgements

I am very grateful for discussions with other participants at the Templeton conferences on the ‘multiverse’ theme in Cambridge in 2001 and Stanford in 2003. My ideas have also been sharpened by e-mail discussions with Robert Mann. This research has been supported in part by the Natural Sciences and Engineering Research Council of Canada.

References

- [1] B. Carter. In *Confrontation of Cosmological Theory with Observational Data*, ed. M. S. Longair (Dordrecht: Reidel, 1974), pp. 291–298.
- [2] B. J. Carr and M. J. Rees. *Nature*, **278** (1979), 605.
- [3] J. D. Barrow and F. J. Tipler. *The Anthropic Cosmological Principle* (Oxford: Clarendon Press, 1986).
- [4] M. Rees. *Just Six Numbers: The Deep Forces that Shape the Universe* (New York: Basic Books, 2000).
- [5] M. J. Duff, B. E. W. Nilsson and C. N. Pope. *Phys. Rep.* **130** (1986), 1.
- [6] R. Bousso and J. Polchinski. *JHEP*, **0006** (2000), 006 [hep-th/0004134].
- [7] S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi. *Phys. Rev. D* **68** (2003), 046005 [hep-th/0301240].
- [8] L. Susskind. This volume (2007) [hep-th/0302219].

- [9] L. Susskind. In *From Fields to Strings: Circumnavigating Theoretical Physics, Ian Kogan Memorial Collection, Vol. 3*, eds. M. Shifman, A. Vainshtein and J. Wheeler (Oxford: Oxford University Press, 2005), pp. 1745–1749 [hep-th/0405189].
- [10] L. Susskind. *The Cosmic Landscape, String Theory and the Illusion of Intelligent Design* (New York: Little, Brown and Company, 2005).
- [11] M. R. Douglas. *JHEP*, **0305** (2003), 046 [hep-th/0303194].
- [12] M. R. Douglas. *Compt. Rend. Phys.* **5** (2004), 965 [hep-th/0401004].
- [13] M. R. Douglas. Understanding the landscape (2006) [hep-th/0602266].
- [14] T. Banks, M. Dine and E. Gorbatov. *JHEP*, **0408** (2004), 058 [hep-th/0309170].
- [15] H. Firouzjahi, S. Sarangi and S. H. H. Tye. *JHEP*, **0409** (2004), 060 [hep-th/0406107].
- [16] D. N. Page. *Int. J. Mod. Phys. D* **5** (1996), 583 [gr-qc/9507024]; also quant-ph/9506010.
- [17] D. N. Page. In *Consciousness, New Philosophical Perspectives*, eds. Q. Smith and A. Jokić (Oxford: Clarendon Press, 2003), pp. 468–506 [quant-ph/0108039].
- [18] R. B. Griffiths. *J. Stat. Phys.* **36** (1984), 219.
- [19] M. Gell-Mann and J. B. Hartle. In *Complexity, Entropy, and the Physics of Information, SFI Studies in the Science of Complexity, Vol. VIII*, ed. W. Zurek (Reading, MA: Addison-Wesley, 1990).
- [20] R. Omnès. *Interpretation of Quantum Mechanics* (Princeton, NJ: Princeton University Press, 1994).
- [21] A. Linde and A. Mezhlumian. *Phys. Rev. D* **53** (1996), 4267 [gr-qc/9511058].
- [22] A. Vilenkin. *Phys. Rev. Lett.* **81** (1998), 5501 [hep-th/9806185].
- [23] A. Vilenkin. *Phys. Rev. D* **59** (1999), 123506 [gr-qc/9902007].
- [24] V. Vanchurin, A. Vilenkin and S. Winitzki. *Phys. Rev. D* **61** (2000), 083507 [gr-qc/9905097].
- [25] J. Garriga and A. Vilenkin. *Phys. Rev. D* **64** (2001), 043511 [gr-qc/0102010].
- [26] J. Garriga and A. Vilenkin. *Phys. Rev. D* **64** (2001), 023507 [gr-qc/0102090].
- [27] J. Garriga and A. Vilenkin. *Phys. Rev. D* **67** (2003), 043503 [astro-ph/0210358].
- [28] M. Tegmark. *Sci. Am.* **288** (5) (2003), 41.
- [29] M. Tegmark. *Spektrum Wiss.* (8) (2003), 34.
- [30] M. Tegmark. In *Science and Ultimate Reality*, eds. J. D. Barrow, P. C. W. Davies and C. L. Harper (Cambridge: Cambridge University Press, 2003) pp. 459–491 [astro-ph/0302131].
- [31] M. Tegmark. *Ann. Phys.* **270** (1998), 1 [gr-qc/9704009].

24

Observation selection theory and cosmological fine-tuning

Nick Bostrom

Faculty of Philosophy, Oxford University

24.1 Introduction

When our measurement instruments sample from only a subspace of the domain that we are seeking to understand, or when they sample with uneven sampling density from the target domain, the resulting data will be affected by a selection effect. If we ignore such selection effects, our conclusions may suffer from selection biases. A classic example of this kind of bias is the election poll taken by the *Literary Digest* in 1936. On the basis of a large survey, the *Digest* predicted that Alf Langdon, the Republican presidential candidate, would win by a large margin. But the actual election resulted in a landslide for the incumbent, Franklin D. Roosevelt. How could such a large sample size produce such a wayward prediction? The *Digest*, it turned out, had harvested the addresses for its survey mainly from telephone books and motor vehicle registries. This introduced a strong selection bias. The poor of the depression era – a group that disproportionally supported Roosevelt – often did not have phones or cars.

The *Literary Digest* suffered a major reputation loss and soon went out of business. It was superseded by a new generation of pollsters, including George Gallup, who not only got the 1936 election right, but also managed to predict what the *Digest's* prediction would be to within 1%, using a sample size that was only one-thousandth as large. The key to his success lay in his accounting for known selection effects. Statistical techniques are now routinely used to correct for many kinds of selection bias.

Observation selection effects are an especially subtle kind of selection effect, introduced not by limitations in our measurement apparatus, but by the fact that all evidence is preconditioned on the existence of an observer ‘having’ the evidence and building the instrument in the first place. Only quite recently have observation selection effects become the subject of

systematic study. Observation selection effects are important in many scientific areas, including cosmology and parts of evolution theory, thermodynamics, the foundations of quantum theory and traffic analysis. There are also interesting applications to the search for extraterrestrial life and questions such as whether we might be living in a computer simulation created by an advanced civilization [1].

Observation selection theory owes a large debt to Brandon Carter, a theoretical physicist who wrote several seminal papers on the subject, the first one published in 1974 [2–4]. Although there were many precursors, one could fairly characterize Carter as the father of observation selection theory – or ‘anthropic reasoning’ as the field is also known. Carter coined the terms ‘weak’ and ‘strong’ anthropic principle, intending them to express injunctions to take observation selection effects into account. But while Carter knew how to apply his principles to good effect, his explanations of the methodology they were meant to embody were less than perfectly clear. The meaning of the anthropic principles was further obscured by some later interpreters, who bestowed them with additional content that had nothing to do with observation selection effects. This contraband content, which was often of a speculative, metaphysical or teleological nature, caused anthropic reasoning to fall into disrepute. Only recently has this trend been reversed.

Since Carter’s contributions, considerable effort has been put into working out the applications of anthropic principles, especially as they pertain to cosmological fine-tuning. There have also been many philosophical investigations into the foundations of anthropic reasoning. These investigations have revealed several serious paradoxes, such as the Doomsday argument (which one may or may not regard as paradoxical) [5], the Sleeping Beauty problem [6, 7], and the Adam and Eve thought experiments [8]. It is still controversial what conclusions we should draw from the apparent fine-tuning of our universe, as well as whether and to what extent our universe really is fine-tuned, and even what it means to say that it is fine-tuned.

Developing a theory of observation selection effects that caters to legitimate scientific needs, while sidestepping philosophical paradoxes, is a non-trivial challenge. In my recent book *Anthropic Bias: Observation Selection Effects in Science and Philosophy* [7], I presented the first mathematically explicit general observation selection theory and explored some of its implications. Before sketching some of the basic elements of this theory and discussing how it pertains to the multiverse hypothesis, let us briefly consider some of the difficulties that confront attempts to create a method for dealing with observation selection effects.

24.2 The need for a probabilistic anthropic principle

The anthropic principles that Carter proposed, even setting aside the inadequacies in their formulation, were insufficiently strong for many scientific applications. A particularly serious shortcoming is that they were not probabilistic.

Carter's principles enable us to deal with some straightforward cases. Consider a simple theory that says that there are one hundred universes, and that ninety of these are lifeless and ten contain observers. What does such a theory predict that we should observe? Clearly not a lifeless universe. Since lifeless universes contain no observers, an observation selection effect precludes them from being observed, as enunciated by the strong anthropic principle. So, although the theory claims that the majority of universes are lifeless, it nevertheless predicts that we should observe one of the atypical ones that contain observers.

Now take a slightly more complicated case. Suppose a theory says that there are one hundred universes of the following description:

ninety type-A universes, which are lifeless;
 nine type-B universes, which contain one million observers each;
 one type-C universe, which contains one billion observers.

What does this theory predict that we should observe? (We need to know the answer to this question in order to determine whether it is confirmed or disconfirmed by our observations.) As before, an obvious observation selection effect precludes type-A universes from being observed, so the theory does not predict that we should observe one of those. But what about type-B and type-C universes? It is logically compatible with the theory that we should be observing a universe of either of these kinds. However, probabilistically it is more likely, conditional on the theory, that we should observe the type-C universe, because that is what the theory says that over 99% of all observers observe. Finding yourself in a type-C universe would, in many cases, tend to confirm such a theory, to at least some degree, compared with other theories that imply that most observers live in type-A or type-B universes.

To obtain this result, we must introduce a probabilistic strengthening of the anthropic principle along the lines of what I have called the 'Self-Sampling Assumption' [7, 9, 10]:

(SSA) One should reason as if one were a random sample from the set of all observers in one's reference class.¹

¹ Related principles have been explored in, for example, refs. [11]–[16]

With the help of SSA, we can calculate the conditional probabilities of us making a particular observation, given one theory or another, by comparing what fraction of the observers in our reference class would be making such observations according to the competing theories.

What SSA does is enable us to take indexical information into account. Consider the following two evidence statements concerning the cosmic microwave background temperature (CMBT):

E: an observation of $\text{CMBT} = 2.7 \text{ K}$ is made.

E*: *we* make an observation of $\text{CMBT} = 2.7 \text{ K}$.

Note that E* implies E, *but not vice versa*: E*, which includes a piece of indexical information, is logically stronger than E. Consequently, it is E* that dictates what we should believe if these different evidence statements lead to different conclusions. This follows from the principle that all relevant information should be taken into account.

Let us examine a case where it is necessary to use E* rather than E [17]. Consider two rival theories about the CMBT at the current cosmic epoch. Let T_1 be the theory we actually hold, claiming that $\text{CMBT} = 2.7 \text{ K}$. Let T_2 say that $\text{CMBT} = 3.1 \text{ K}$. Now suppose that our universe is infinitely large and contains an infinite number of stochastic processes of suitable kinds, such as radiating black holes. If for each such random process there is a finite, non-zero probability that it will produce an observer in any particular brain-state (subjectively making an observation e), then, because there are infinitely many independent ‘trials’, the probability for any given observation e that e will be made by some observer somewhere in our universe is equal to unity. Let B be the proposition that this is the case. We might wonder how we could possibly test a conjunction like $T_1 \& B$ or $T_2 \& B$. For whatever observation e we make, both these conjunctions predict equally well (with probability unity) that e should be made. According to Bayes’s theorem, this entails that conditionalizing on e being made will not affect the probability of $T_1 \& B$ or $T_2 \& B$. And yet it is obvious that the observations we have actually made support $T_1 \& B$ over $T_2 \& B$. For, needless to say, it is because of our observations that we believe that $\text{CMBT} = 2.7 \text{ K}$ and not 3.1 K .

This problem is solved by going to the stronger evidence statement E* and applying SSA. For any reasonable choice of reference class, $T_1 \& B$ implies that a much larger fraction of all observers in that class should observe $\text{CMBT} = 2.7 \text{ K}$ than does $T_2 \& B$. (According to $T_1 \& B$, all normal observers observe $\text{CMBT} = 2.7 \text{ K}$, while $T_2 \& B$ implies that only some exceptional black-hole-emitted observers, or those who suffer from rare illusions, observe

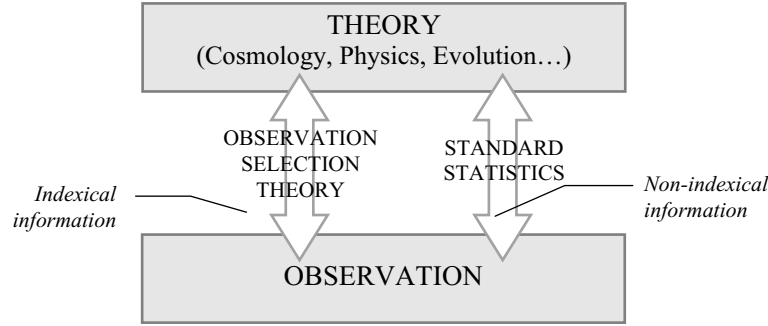


Fig. 24.1. Observation selection theory complements standard statistics and is required for cases where either the evidence or the hypothesis includes indexical information.

CMBT = 2.7 K.) Given these facts, SSA implies

$$P(E^*|T_1 \& B) \gg P(E^*|T_2 \& B). \quad (24.1)$$

From Eq. (24.1), it is then easy to show that our actual evidence E^* does indeed give us reason to believe in $T_1 \& B$ rather than $T_2 \& B$. In other words, SSA makes it possible for us to know that CMBT = 2.7 K. This is illustrated in Fig. 24.1.

For the moment, we are setting aside the problem of exactly how the reference class is to be defined. In the above example, any reference class definition satisfying some very weak constraints would do the trick. To keep things simple, we also ignore the problem of how to generalize SSA to deal with infinite domains. Strictly speaking, such an extension, which might involve focusing on densities rather than sets of observers, would be necessary to handle the present example, but it would add complications that would distract from basic principles.

24.3 Challenges for observation selection theory

So far, so good. SSA can derive additional support from various thought experiments, and it can be applied to a number of scientific problems where it yields results that are less obvious but nevertheless valid.

Unfortunately, if we use SSA with the universal reference class, the one consisting of all intelligent observers, we encounter paradoxes. One of these is the notorious Doomsday argument, which purports to show that we have systematically underestimated the probability that our species will become extinct soon. The basic idea behind this argument is that our position in the sequence of all humans that will ever have lived would be much more

probable if the total number of humans is, say, 200 billion rather than 200 trillion. Once we take into account this difference in the conditional probability of our observed birth rank, the argument goes, hypotheses that imply that very many humans are yet to be born are seen to be much less probable than we would have thought if we considered only the ordinary evidence (about the risk of germ warfare, nuclear war, meteor strikes, destructive nanotechnology, etc.). The prospects of our descendants ever colonizing the Galaxy would be truly dismal, as this would make our own place in human history radically atypical.

The most common initial reaction to the Doomsday argument is that it must be wrong; moreover, that it is wrong for some obvious reason. Yet when it comes to explaining *why* it is wrong, it turns out that there are almost as many explanations as there are people who disbelieve the Doomsday arguments. And the explanations tend to be mutually inconsistent. On closer inspection, all these objections, which allege some trivial fallacy, turn out to be themselves mistaken [5, 7, 18].

Nevertheless, the Doomsday argument has some backers, and while the way in which it aims to derive its conclusion is definitely counter-intuitive, it may not quite qualify as a paradox. It is therefore useful to consider the following thought experiment [8], which has a structure similar to the Doomsday argument but yields a conclusion that is even harder to accept.

Serpent's Advice. Eve and Adam, the first two humans, knew that if they gratified their flesh, Eve might bear a child, and that if she did, they would both be expelled from Eden and go on to spawn billions of progeny that would fill the Earth with misery. One day a serpent approached the couple and spoke thus: 'Psssst! If you take each other in carnal embrace, then either Eve will have a child or she won't. If she has a child, you will have been among the first two out of billions of people. Your conditional probability of having such early positions in the human species, given this hypothesis, is extremely small. If, on the other hand, Eve does not become pregnant, then the conditional probability, given this, of you being among the first two humans is equal to one. By Bayes's theorem, the risk that she shall bear a child is less than one in a billion. Therefore, my dear friends, step to it and worry not about the consequences!'

It is easy to verify that, if we apply SSA to the universal reference class, the serpent's mathematics is watertight. Yet surely it would be irrational for Eve to conclude that the risk of her becoming pregnant is negligible.

One can try to revise SSA in various ways or to impose stringent conditions on its applicability. However, it is difficult to find a principle that satisfies all constraints that an observation selection theory ought to satisfy – a

principle that both serves to legitimize scientific needs and at the same time is probabilistically coherent and paradox-free. We lack the space here to elaborate on the multitude of such theory constraints. It is easy enough to formulate a theory that passes a few of these tests, but it is hard to find one that survives them all.

24.4 Sketch of a solution

The solution, in my view, begins with the realization that the problem with SSA is not that it is too strong but that it is not strong enough. SSA tells you to take into account one kind of indexical information: information about which observer you are. But you have more indexical information than that. You also know *which temporal segment* of that observer, which ‘observer-moment’, you currently are. We can formulate a ‘Strong Self-Sampling Assumption’ that takes this information into account as follows [7]:

(SSSA) Each observer-moment should reason as if it were randomly selected from the class of all observer-moments in its reference class.

Arguments can be given for why SSSA expresses a correct way of reasoning about a number of cases.

To cut a long story short, we find that the added analytical firepower provided by SSSA makes it possible to relativize the reference class, so that different observer-moments of the same observer may place themselves in different reference classes without that observer being probabilistically incoherent over time. This relativization of the reference class, in turn, makes it possible coherently to reject the serpent’s advice to Eve, while still enabling legitimate scientific inferences to go through. Recall, for instance, the case we considered above, about our observation of $\text{CMBT} = 2.7 \text{ K}$, supporting the theory that this is the actual local temperature even when evaluated in the context of a cosmological theory that asserts that all possible human observations are made. This result would be obtained almost independently of how we defined the reference class. So long as the reference class satisfies some very weak constraints, the inference works. This ‘robustness’ of an inference under different definitions of the reference class turns out to be a hallmark of those applications of anthropic reasoning that are scientifically respectable. By contrast, the applications that yield paradoxes rely on specific definitions of the reference class and collapse when a different reference class is chosen. The serpent’s reasoning, for example, works only if we place the observer-moments of Adam and Eve prior to sinning in the same reference class as the observer-moments of those (very different) observers

that may come to exist centuries later as a result of the first couple's moral lapse. The very fact that this absurd consequence would follow from selecting such a reference class gives us a good reason to use another reference class instead.

The idea expressed vaguely in SSSA can be formalized into a precise principle that specifies the evidential bearing of a body of evidence e on a hypothesis h . I have dubbed this the 'Observation Equation' [7]:

$$P_\alpha(h|e) = \frac{1}{\gamma} \sum_{\sigma \in \Omega_h \cap \Omega_e} \frac{P_\alpha(w_\sigma)}{|\Omega_\alpha \cap \Omega(w_\sigma)|}. \quad (24.2)$$

Here α is the observer-moment whose subjective probability function is P_α , Ω_h is the class of all possible observer-moments about whom h is true, Ω_e is the class of all possible observer-moments about whom e is true, Ω_α is the class of all observer-moments that α places in the same reference class as herself, w_α is the possible world in which α is located, and γ is a normalization constant. The quantity in the denominator is the cardinality of the intersection of two classes, Ω_α and $\Omega(w_\sigma)$, the latter being the class of all observer-moments that exist in the possible world w_σ .

The Observation Equation can be generalized to allow for different observer-moments within the reference class having different weights $\mu(\sigma)$. This option is of particular relevance in the context of the 'many worlds' version of quantum mechanics, where the weight of an observer-moment would be proportional to the amplitude squared of the branch of the universal wave-function where that observer-moment lives.

The Observation Equation expresses the core of a quite general methodological principle. Two of its features deserve to be highlighted here. The first is that by dividing the terms of the sum by the denominator, we are factoring out the fact that some possible worlds contain more observer-moments than do others. If one omitted this operation, one would, in effect, assign a higher prior probability to possible worlds that contain a greater number of observers (or more long-lived observers). This would be equivalent to accepting the Self-Indication Assumption, which prescribes an *a priori* bias towards worlds that have a greater population. But, although the Self-Indication Assumption has its defenders (see, e.g., ref. [19]), it leads to paradoxical consequences, as shown by the Presumptuous Philosopher thought experiment [7]. In a nutshell, this thought experiment points out that the Self-Indication Assumption implies that we should assign probability one to the cosmos being infinite, even if we had strong empirical evidence that it was finite; and this implication is very hard to accept.

A second feature to highlight is that the only possible observer-moments that are taken into account by an agent are those that the agent places in the same reference class as herself. Observer-moments that are outside this reference class are treated, in a certain sense, as if they were rocks or other lifeless objects. Thus, the question of how to define ‘observer’ is replaced by the question of how an agent should select an appropriate reference class for a particular application. This reference class will often be a proper subset of intelligent observers or observer-moments.

Bounds can be established on permissible definitions of the reference class. For example, if we reject the serpent’s advice, we must not use the universal reference class that places all observer-moments in the same reference class. If we want to conclude on the basis of our evidence that $\text{CMBT} = 2.7 \text{ K}$, we must not use the minimal reference class that includes only subjectively indistinguishable observer-moments, for such a reference class would block that inference.

It is an open question whether additional constraints can be found that would always guarantee the selection of a unique reference class for all observer-moments, or whether there might instead, as seems quite likely, be an unavoidable element of subjective judgment in the choice of reference class. This latter contingency would parallel the widely acknowledged element of subjectivity inherent in many other kinds of scientific judgments that are made on the basis of limited or ambiguous evidence.

24.5 Implications for cosmological fine-tuning

One immediate implication of observation selection theory for cosmological fine-tuning is that it allays worries that anthropic reasoning is fundamentally unsound and inevitably plagued by paradoxes. It thereby puts the multiverse explanation of fine-tuning on a more secure methodological footing.

A multiverse theory can potentially explain cosmological fine-tuning, provided several conditions are met. To begin with, the theory must assert the existence of an ensemble of physically real universes. The universes in this ensemble would have to differ from one another with respect to the values of the fine-tuned parameters, according to a suitably broad distribution. If observers can exist only in those universes in which the relevant parameters take on the observed fine-tuned values (or if the theory at least implies that a large portion of all observers are likely to live in such universes), then an observation selection effect can be invoked to explain why we observe a fine-tuned universe. Moreover, in order for the explanation to

be completely satisfactory, this postulated multiverse should not itself be significantly fine-tuned. Otherwise the explanatory problem would merely have been postponed; for we would then have to ask, how come the *multiverse* is fine-tuned? A multiverse theory meeting these conditions could give a relatively high conditional probability to our observing a fine-tuned universe. It would thereby gain a measure of evidential support from the finding that our universe is fine-tuned. Such a theory could also help *explain* why we find ourselves in a fine-tuned universe, but to do this the theory would also have to meet the ordinary crew of *desiderata* – it would have to be physically plausible, fit the evidence, be relatively simple and non-gerrymandered, and so forth. Determining whether this potential anthropic explanation of fine-tuning actually succeeds requires a lot of detailed work in empirical cosmology.

One may wonder whether these conclusions depend on fine-tuning *per se* or whether they follow directly from the generic methodological injunction that we should, other things being equal, prefer simpler theories with fewer free variables to more complex theories that require a larger number of independent stipulations to fix their parameters (Ockham's razor). In other words, how does the fact that *life would not have existed if the constants of our universe had been slightly different* play a role in making fine-tuning cry out for an explanation and in suggesting a multiverse theory as the remedy?

Observation selection theory helps us answer these questions. It is not just that all single-universe theories in the offing would seem to require delicate handpicking of lots of independent variable values that would make such theories unsatisfactory – the fact that life would not otherwise have existed adds to the support for a multiverse theory. It does so by making the anthropic multiverse explanation possible. A simple multiverse theory could potentially give a high conditional probability to us observing the kind of universe we do, because it says that only that kind of universe – among all the universes in a multiverse – would be observed (or, at least, that it would be observed by a disproportionately large fraction of the observers). The observation selection effect operating on the fact of fine-tuning *concentrates* the conditional probability on us observing a universe like the one we live in. This is illustrated by Fig. 24.2.

Further, observation selection theory enables us to answer the question of how big a multiverse has to be in order to explain our evidence. The upshot is that bigger is not always better [7]. The postulated multiverse would have to be large and varied enough to make it probable that some universe like ours should exist. Once this objective is reached, there is no additional

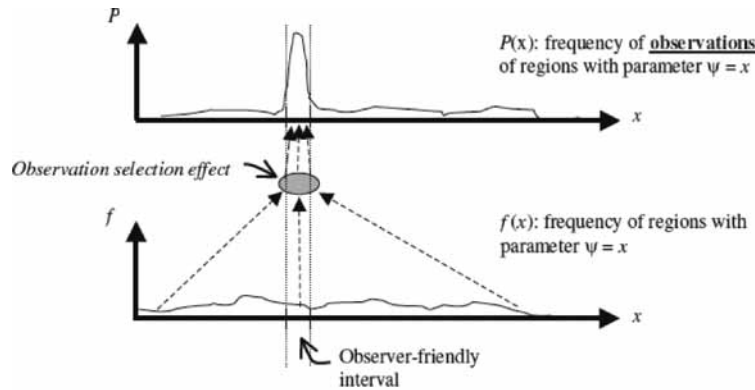


Fig. 24.2. An observation selection acts like a focusing lens, concentrating conditional probability on a small set of observational parameter values.

anthropic ground for thinking that a theory that postulates an even bigger ensemble of universes is therefore, other things equal, more probable. The choice between two multiverse theories that both give a high probability to a fine-tuned universe like ours existing must be made on other grounds, such as simplicity or how well they fit with the rest of physics.

A multiverse would not have to be large enough to make it probable that a universe *exactly* like ours should exist. A multiverse theory that entails such a huge cosmos that one would expect a universe exactly like ours to be included in it does not have an automatic advantage over a more frugal competitor. Such an advantage would have to be earned, for example by being a simpler theory. There is, as we noted earlier, no general reason for assigning a higher probability to theories that entail that there is a greater number of observers in our reference class. Increasing the membership in our reference class might make it more likely that the reference class should contain some observer who is making exactly the observations that we are making, but it would also make it more surprising that we should happen to be that particular observer rather than one of the others in the reference class. The net effect of these two considerations is to cancel each other out. All the observation selection effect does is concentrate conditional probability on the observations represented by the observer-moments in our reference class so that, metaphorically speaking, we can postulate stuff outside the reference class ‘for free’. Postulating additional stuff *within* the reference class is not *gratis* in the same way, but would have to be justified on independent grounds.

It is, consequently, in major part an empirical question whether a multiverse theory is more plausible than a single-universe theory, and whether a

larger multiverse is more plausible than a smaller one. Anthropic considerations are an essential part of the methodology for addressing these questions, but the answers will depend on the data.

In its current stage of development, observation selection theory falls silent on problems where the solution depends sensitively on the choice of reference class. For example, suppose a theory implies that the overwhelming majority of all observers that exist are of a very different kind from us. Should these radically different observers be in our reference class? If we do place them in our reference class (or, more precisely, if we place their observer-moments in the same reference class as our own current observer-moments), then a theory that implies that the overwhelming majority of all observers are of that different kind would be contra-indicated by our evidence, roughly because – according to that theory – we should have thought it highly unlikely that we should have found ourselves to be the kind of observer that we are rather than a more typical kind of observer. That is to say, such a theory would be disconfirmed compared to an equally simple theory that implied that a much larger fraction of all observers would be of our kind. Yet if we exclude the other kind of observer from our reference class, our evidence would not count against the theory. In a case like this, the choice of reference class makes a difference to our interpretation of our evidence.

Further developments of observation selection theory would be needed to determine whether there is a unique objectively correct way of resolving such cases. In the meantime, it is a virtue of the methodological framework encapsulated by the Observation Equation that it brings this indeterminacy into the open and does not surreptitiously privilege one particular reference class over potentially equally defensible alternatives.

References

- [1] N. Bostrom. Are you living in a computer simulation? *Phil. Quart.* **53** (2003), 243.
- [2] B. Carter. Large number coincidences and the anthropic principle in cosmology. In *Confrontation of Cosmological Theories with Data*, ed. M.S. Longair (Dordrecht: Reidel, 1974), pp. 291–298.
- [3] B. Carter. The anthropic principle and its implications for biological evolution. *Phil. Trans. Roy. Soc. A* **310** (1983), 347
- [4] B. Carter. The anthropic selection principle and the ultra-Darwinian synthesis. In *The Anthropic Principle*, eds. F. Bertola and U. Curi (Cambridge: Cambridge University Press, 1989), pp. 33–63.
- [5] N. Bostrom. The doomsday argument is alive and kicking. *Mind*, **108** (1999), 539.

- [6] N. Bostrom. Sleeping beauty and self-location: a hybrid model. *Synthese* (2006); ?p=4874127141594c5a946b4bee5b859f3fdpi=1.
- [7] N. Bostrom. *Anthropic Bias: Observation Selection Effects in Science and Philosophy* (New York: Routledge, 2002).
- [8] N. Bostrom. The doomsday argument, Adam & Eve, UN++, and Quantum Joe. *Synthese* **127** (2001), 359.
- [9] N. Bostrom. Investigations into the doomsday argument. (1997) <http://www.anthropic-principles.com/preprints/inv/investigations.html>.
- [10] N. Bostrom. Observer-relative chances in anthropic reasoning? *Erkenntnis*, **52** (2000), 93.
- [11] R. J. Gott. Implications of the Copernican Principle for our future prospects. *Nature*, **363** (1993), 315.
- [12] A. Vilenkin. Predictions from quantum cosmology. *Phys. Rev. Lett.* **74** (1995), 846.
- [13] D. N. Page. Sensible quantum mechanics: Are probabilities only in the mind? *Int. J. Mod. Phys. D* **5** (1996), 583.
- [14] D. N Page. Can quantum cosmology give observational consequences of many-worlds quantum theory? In *General Relativity and Relativistic Astrophysics, 8th Canadian Conference*, eds. C. P. Burgess and R. C. Myers (Melville, New York: American Institute of Physics, 1999), pp. 225–232.
- [15] M. Tegmark. Is the ‘Theory of Everything’ merely the ultimate ensemble theory? *Ann. Phys.* **270** (1998), 1 [gr-gc/9704009].
- [16] A. Linde and A. Mezhlumian. On regularization scheme dependence of predictions in inflationary cosmology. *Phys. Rev. D* **53** (1996), 4267.
- [17] N. Bostrom. Self-locating belief in big worlds: Cosmology’s missing link to observation. *J. Phil.* **99**, (2002), 607623.
- [18] J. Leslie. *The End of the World: The Science and Ethics of Human Extinction* (London: Routledge, 1996).
- [19] K. Olum. The Doomsday argument and the number of possible observers. *Phil. Quart.* **52** (2002), 164.

Are anthropic arguments, involving multiverses and beyond, legitimate?¹

William R. Stoeger, S. J.

Vatican Observatory Research Group, Steward Observatory, University of Arizona

AQ: Please check 'S. J.' in the author name

25.1 Introduction

Though there has been much discussion of the Anthropic Principle (AP) over the last 35 years or so, it is still a very tantalizing and controversial subject, on the boundary between scientific cosmology and philosophy. As new scenarios and theories emerge for describing and explaining the origin of our observable universe, AP considerations inevitably surface. So, a critical review of the meaning and status of the AP – as well as of the directions anthropic arguments are now taking, their legitimacy and the fundamental philosophical issues involved – is perhaps warranted.

The anthropic idea was first introduced in 1961 by Robert Dicke, who noted the comparability of several very large numbers when fundamental physical constants are combined, and suggested that this might be connected with the conditions necessary for the presence of observers [1]. A decade later, Barry Collins and Stephen Hawking, realizing that the initial conditions for our universe seemed to be very special, suggested the following: ‘The fact that we have observed the universe to be isotropic is therefore only a consequence of our own existence’ [2]. One way of explaining this, they speculated, would be to have an ‘infinite set of universes with all possible initial conditions’ – thus anticipating the way many cosmologists now interpret the AP.

The following year, Brandon Carter – obviously stimulated by Dicke’s seminal suggestion, since he referred to it several times in his paper – introduced the term ‘anthropic principle’. His initial formulation of the AP was as follows: ‘What we can expect to observe must be restricted by the conditions necessary for our presence as observers’ [3]. Subsequently, Carter

¹ This is a revised and expanded version of an article, ‘The Anthropic Principle revisited’, which appeared in *Phil. Sci.* **10** (2003), 9–33. Published here with permission.

made a distinction between the ‘weak’ and ‘strong’ forms of the AP [4]. However, these terms have been used in many different ways, corresponding to similar but inequivalent formulations of the AP, which has led to considerable confusion. (In summarizing the origin and early history of the AP, I have followed ref. [5].)

First, it is important to recognize that the AP is not really a principle. Its fundamental content is that our universe *appears* to be fine-tuned for life and for consciousness – or perhaps, more precisely, for complexity. This appearance of fine-tuning originates from analysis of and reflection upon the results of a very broad range of experimental and theoretical investigations, indicating the extreme sensitivity of our universe’s capacity for generating and sustaining complexity to very small changes in the laws and constants of nature, in the properties of the basic constituents of matter and in the initial conditions of our universe (for example the expansion rate or mass–energy density at some early time). A classical compendium on the AP, including a wide range of examples of fine-tuning, is given in ref. [6]. Changing the value of any of a large number of parameters even a little would so change our universe as to preclude the emergence of complexity – and therefore life and consciousness. The different formulations of the AP – and all the controversy which surrounds it – really trace back to the issue of what conclusions can be legitimately drawn from this apparent fine-tuning and what presuppositions are justifiable.

25.2 Weak and strong versions of the AP

From the earliest AP discussions, it was recognized that there are both weak (WAP) and strong (SAP) formulations. The weak versions assert that, since there are observers in our universe, its characteristics, including the values of the fundamental constants and the initial conditions, must be consistent with the presence of such observers (see ref. [5], p. 372). Thus the existence of observers acts *a posteriori* to select values of the fundamental constants and other important parameters. These versions of the AP just specify the conditions which have been fulfilled for complexity and life to arise – they do not explain how or why those conditions have been realized. In fact, some writers describe the WAP as just a selection effect.

Strong versions of the AP go much further: they assert that our universe – right from the start – *had* to be such that the appearance of observers is inevitable. That is, they purport to account in a basic way for our universe being life-bearing. For instance, one version of the SAP would be as follows: ‘The universe must be such as to admit the existence of observers within it at some stage’ (see ref. [5], p. 376). Here, the words ‘must be’ indicate

a priori necessity – not the consequence of there being observers now [5]. The eventual emergence of observers somehow explains why the universe possessed its initial characteristics – it has these characteristics *in order* that observers will appear.

From this, it is clear that some evidence or justification for the requirement of having observers must be provided. Many – but not all – such formulations do this by incorporating an explicit or implicit finality or purposiveness in our universe, which goes considerably beyond what can be concluded from the natural sciences themselves. Sometimes this is done on philosophical grounds, sometimes on theological ones.

25.3 Two principal versions of the SAP

Over the past decade, two very different – and certainly inequivalent – versions of the SAP have been discussed. The first is essentially the way it was first formulated: the characteristics of our universe are chosen to ensure the appearance of life and observers. But this raises the issue of what or who tailors the laws of nature and the fundamental constants in this way, which immediately goes beyond the domain of science.

Thus, a second version of the SAP has become popular, which – at first sight – keeps it within the realm of the natural sciences. This asserts that our universe – or our domain – is one of a large, actually existing, ensemble of universes or domains, each having different laws, fundamental constants and initial conditions. In fact, a frequent, but much less adequate, specification of this ensemble is that it contains all possible universes. The presupposition here is that there exist universes or domains representing the full range of possibilities [7]. There is then some probability that any one of the these really existing universes will allow the emergence of life and observers.

This, in one sense, *does* explain why our universe is life-bearing, providing the presuppositions can be justified and providing a meaningful probability measure can be defined on the space of the ensemble [7,8]. But this explanation is obviously incomplete. It immediately invites further understanding of the process by which this particular cosmic ensemble emerged and why it contains universes or domains which allow for the emergence of complexity. And if we can substantiate the operation of such a fertile cosmogonic process, then we may certainly want to seek an explanation for its origin, however we have come to understand and model its scientifically accessible underpinnings.

Thus, this formulation of the second version of the SAP clearly manifests its inequivalence with the first version, as well as the extraordinarily strong

presuppositions on which it rests. In fact, if we use it to argue from the presence of observers in our universe to the existence of a certain type of ensemble of universes, then it seems to reduce to the WAP. However, the characteristic feature of this version – the existence of at least a large subset of possible domains, some of which are life-bearing – really takes us beyond the WAP. It solves the fine-tuning problem, but does not explain in any *a priori* way why our universe should have observers in it at some stage, much less why the ensemble of all existing universes should include some which admit their emergence.

It is certainly true that, if the ensemble exists, then our universe itself *must* exist. But this is obviously a very weak form of the SAP. The ‘necessity’ of the existence of our life-bearing universe rests on the presupposed existence of all possible universes, or at least of a large number of universes of a broad range of types. Clearly – to achieve equivalence with the first version of the SAP – we require an adequate explanation for the necessity of the encompassing ensemble – or at least some explanation or justification for its *de facto* realization. Anchoring this version of the SAP really requires some compelling cosmological account of the ensemble, which is by no means unique [8], or – even better – of why it *must* exist. This would make the multiverse version of the SAP equivalent to the first version. However, the multiverse version will never be able to go that far, since it strives to avoid scientifically inaccessible causes and explanations.

Another strong reason for stressing the multiverse version of the SAP is that we now recognize that there are a number of natural ways in which an ensemble of actually existing ‘universes’ could arise in quantum cosmology: for example, Andrei Linde’s chaotic or eternal inflation scenario [9]. However, as we shall see later, such suggestions are not yet very secure. Furthermore, there are serious physical and philosophical issues which need to be resolved before they can be regarded as evidential [7, 8]. Until then, this version of the SAP, despite its popularity, must be relegated to the category of (at best) informed cosmological speculation.

In discussing the multiverse version of the SAP more fully, several points should be emphasized.

- As it now stands, it does not provide either an adequate or complete – let alone an ultimate – scientific explanation. Only strong evidence for – and an adequate description of – the process by which the ensemble emerges can do that. To constitute an ultimate explanation, that process must further be shown to be necessary, an understandable accident that was always a possibility, or intended by some transcendent agent for a specific

reason. But the scenarios by which the ensembles may have originated are still very uncertain and *ad hoc*, so it is impossible to envision them as necessary or providing any fundamental or final philosophical explanation.

- Once we grant that the ensemble embracing our universe really does exist, then saying this ensemble explains how our universe is fine-tuned for life does have some meaning and validity – in terms of the probability of any one of the universes being like our own. But this requires that there be some well defined distribution function on the space of all possible universes, with an associated probability measure [7,8].
- It is very difficult, if not impossible, to define a really existing ensemble of all possible universes in a meaningful way which avoids infinities [7,8]. Also, in order for the ensemble idea to work, it cannot just be an ensemble of conceptually possible universes – it must really exist. Any power this version possesses relies on the universes or domains having a *bona fide* existence. Possible or potential existence has no *a posteriori* implications and explains nothing (see ref. [5], p. 371).

25.4 Scientific status of ensembles of universes

We have seen that the cosmic ensemble version of the SAP is not as strong as the original version. It is incomplete, requiring understanding of the process generating the ensemble. Furthermore, even with this understanding it cannot provide an ultimate explanation of the fine-tuning. Nevertheless, we can accept it such as it is, acknowledging that it may become more compelling as our understanding of the early universe improves. With this in mind, we shall reflect in more detail on what has come to be known as the ‘multiverse’ proposal [7].

First, as emphasized in Section 25.3, there are well supported but still preliminary indications that whatever process or event gave birth to our universe or domain also generated a large number of other universes or domains. This is why so many cosmologists and theoretical physicists are taking the idea seriously. Several lines of current research and speculation are probing, accumulating evidence for and attempting to model the primordial emergence of such an ensemble. Besides Linde’s chaotic inflationary programme, there are a number of others, including those of Steven Weinberg [12,13] and Jaume Garriga and Alex Vilenkin [14–16], who have suggested that random quantum fluctuations generated during inflation could have led to a large number of different cosmic regions, each with a different vacuum energy density. All of them would then evolve differently, with significantly different physics perhaps emerging in subsequent (GUT and electro-weak)

spontaneous-symmetry-breaking transitions. Recently, superstring theory has provided prospects for generating multiverses. Some versions of it provide ‘landscapes’ populated by extremely large numbers of vacua, each of which could initiate a separate universe domain [17–20].

Ensembles of universes can also be generated in many other ways: for example, through decoherence from the mixed quantum gravity states which may have characterized the Planck era, or through the re-expansion into different domains of regions which had earlier collapsed to form black holes [21]. In the latter case, Lee Smolin envisions a type of natural selection operating on the resulting ensemble of expanding regions, rendering a significant subset of them bio-friendly. Finally, ensembles of universes can develop from the cosmic branching allowed by the Everett–Wheeler interpretation of quantum theory. In a recent popular article [22], Max Tegmark presents the case for multiverses and describes the different processes through which they may arise. All such scenarios are scientifically plausible. But, if they are to be taken seriously, they must continue to receive support from theoretical and observational advances in early and late universe research.

Even when such multiverse scenarios are better established, their deployment in anthropic arguments requires a proper characterization of the ensembles, with well defined (finite) probability distribution functions and meaningful probability measures [7]. If all these requirements are eventually fulfilled, there still remains the philosophical question of the legitimacy of appealing to ensembles whose existence is not testable. This raises the more fundamental issue of what kinds of testability are appropriate in the natural sciences. What concept of testability, if any, can legitimate reliance on cosmic ensembles for scientific conclusions? It is important in this regard to note that there is a general consensus that the acceptability of any appeal to multiverses depends on there being a testable theory which independently predicts their existence. This requirement is crucial and must be kept in mind in evaluating these theories and in contemplating their use in anthropic arguments.

That understood, are there concepts of testability which would enable multiverses to be scientifically legitimate? I believe that there are. One very compelling approach is that of ‘retroduction’ or ‘abduction’, first described in detail by the American philosopher of science C. S. Peirce [23, 24] and more recently emphasized by Ernan McMullin [25–28]. ‘Retroduction’ is inference from observed consequences of a postulated hypothesis to the explanatory antecedents contained in the hypothesis – that is, it is an inference based on the success or fruitfulness of an hypothesis in accounting for and better understanding a set of phenomena. Scientists construct

hypotheses, which are then used to describe and probe the phenomena more profoundly. As they do so, they modify – or even replace – the original hypotheses in order to make them more fruitful and more precise in what they reveal and explain. As McMullin himself emphasizes, the hypotheses may often involve the existence of hidden properties or entities (like multiverses) which are basic to the explanatory power they possess. As the hypotheses become more fruitful in explaining a set of natural phenomena and their inter-relationships, and more central to the research of a given discipline, they become more reliable as accounts of reality. Even if the hidden properties are never directly detected, the success of the hypotheses which rely on them indirectly leads us to affirm that either they – or something very much like them – must exist. We can regard hypotheses as fruitful or successful if they: (1) account for all relevant data (empirical adequacy); (2) provide *long-term* explanatory success and stimulate productive lines of further enquiry (theory fertility); (3) establish the compatibility of previously disparate domains of phenomena or facts (unifying power); and (4) manifest consistency (or correlation) with other established theories [29].

This way of looking at how science works provides us with a criterion for testing theories which imply the existence of a multiverse. If such a theory successfully explains various aspects of what we see and measure in our universe, and continues to provide a secure basis for further cosmological understanding, then that strongly supports the existence of such universes, even though we may never be able to detect them directly. This criterion can be summarized as: Does the multiverse theory lead to greater intelligibility of the reality around us?

25.5 Using anthropic arguments in scientific cosmology

Setting aside for the time being the controversial SAP and multiverse ideas, we now turn our attention to a more modest application of anthropic arguments: their use in deciding purely scientific issues in cosmology. The extreme sensitivity of the character of our universe to slight changes in fundamental constants, the properties of fields and particles, initial conditions, etc. shows that – with enough knowledge – we can determine the values of these parameters on anthropic grounds.

The general form of such arguments is very straightforward. For life to exist in our universe, a given parameter A must be in the range A_1 to A_2 . Life exists in our universe; therefore the value of A is between A_1 and A_2 . However, it is important to recognize that this is a *necessary* but not *sufficient* condition for life. The main idea is that, using such anthropic

arguments, cosmology can determine the values of key parameters without directly measuring them. This would be important whenever we did not have the capability of measuring the parameter A .

Three questions arise in considering such arguments: (1) Are they legitimate? (2) Do we need them in cosmology? (3) Do they suffice from a scientific point of view? The first question is easy to answer – the logic of the argument is clearly valid, so anthropic arguments are certainly legitimate. Establishing the major premise requires a great deal of theoretical work, however, and usually involves assumptions about what is essential for the emergence of life and how those essentials can be realized. Furthermore, as discussed below, such arguments demand a more complete understanding of the underlying ‘laws of nature’ which are at the basis of the parameter constraints.

Moving to the second question, we can say that, in some circumstances, we may ‘need’ such arguments or at least find them ‘useful’ until better scientific evidence is available. One of the drawbacks of anthropic arguments is that establishing that a given parameter must have a certain range of values for life normally takes a great deal of scientific investigation. The better and more reliable the underlying scientific theory enabling us to make that determination, the better and more reliable the anthropic arguments we can construct. But often, by the time we have reached that stage, we already know or have a good idea of what range of values a certain parameter has, independently of anthropic arguments. From this we might conclude that, whatever the state of our knowledge, anthropic arguments can always serve as consistency checks on conclusions we have reached by other means.

The answer to the third question – Are anthropic arguments sufficient? – is obviously no from a scientific point of view. The anthropic connection never stands by itself, but reflects a deeper and more fundamental set of relationships in the laws of nature – whether or not we understand them. Those deeper and more fundamental relationships will always be vulnerable to scientific determination or philosophical reflection, at least in principle.

25.6 Undermining anthropic arguments

The difficulty of reliably establishing the ranges of parameter values necessary for life in our universe is illustrated by the work of Anthony Aguirre [30]. He has demonstrated that there are more regions of cosmological parameter space which allow life than we had originally suspected. And some of these regions are isolated from each other.

This is true, for instance, for the cosmological parameter η , which is the ratio of the number density of baryons (protons and neutrons) to the number density of photons. This is a measure of the cosmological entropy density. In our universe, $\eta \approx 10^{-9}$, which indicates that the early universe was very hot. If we found $\eta \approx 1$ instead, our universe would have started out relatively cold. Such universes are referred to as ‘cold big bang’ models. Aguirre has shown that several classes of such models allow the formation of stars, and hence the production of heavy elements, and would therefore be open to the emergence of life. This set of bio-friendly cosmological models is disconnected in η -parameter space from the hot big bang models.

This unexpected development undermines anthropic arguments somewhat – or at least makes the conclusions we can draw from them less certain. We originally expected anthropic arguments to yield tightly constrained parameter ranges for life. But now, in at least some cases, we find that these ranges are somewhat broader and perhaps even disconnected from one another. We do not know if there are other cases of this sort. But if we are going to rely on such arguments, we have to be sure that we have theoretically explored the full range of cosmological parameter space for isolated bio-friendly islands.

Despite this uncertainty, we can still legitimately assert that: (1) the conditions for life have been fulfilled; and (2) the values of the parameters which characterize our universe must fall within certain relatively narrow ranges for these conditions to be maintained. However, given Aguirre’s results, we need to be cautious in asserting precisely what these bio-friendly ranges are.

25.7 The SAP, final theories and alternative universes

Any version of the SAP presupposes that the laws of nature that characterize our universe could have been significantly different in terms of at least one of the following: initial conditions, particle properties (for example masses), fundamental constants (for example coupling parameters) and laws of nature (for example different fundamental interactions). The key point is this: if a ‘final theory’ or ‘a theory of everything’ specifies a unique universe – that is, a universe with precise laws, values of the fundamental constants and initial conditions – then there is no need for, or even the possibility of, anthropic arguments. The universe could not have been any different without violating the theoretical consistency ‘imposed’ by the final theory. However, even if this were the case, we would – from most philosophical points of view – still

need a sufficient explanation for the existence of the universe and for its precise order.

The extreme consequence of a final theory that specified a unique universe, accounting for all its characteristics precisely and exhaustively, is difficult to imagine. It is just possible that a final theory could achieve this. However, it seems very unlikely that it would fully determine the conditions for the universe as it exited the Planck or inflationary era, for example its expansion rate at this point and the initial entropy. In other words, to make anthropic arguments unnecessary scientifically or vacuous philosophically, we would need an adequate theory of initial conditions. We would also need a theory to specify the parameter values after spontaneous symmetry-breaking transitions.

An alternative would be a process, or a combination of processes, which renders the universe which emerges from the quantum cosmological womb *insensitive* to initial conditions. If such processes operated in the early universe, there would be no need for us to know or to explain the initial conditions in order to model how our universe evolved to its present form. It would have done so, no matter what the initial conditions, due to the ‘smoothing’ action of these primordial processes. They would bring the infant universe to the primordial homogeneity, no matter how it ‘began’. This attractive suggestion is sometimes referred to as the ‘Cosmological Indifference Principle’ (see ref. [5], p. 359).

Two proposals for such ‘indifference-rendering’ are the chaotic cosmology programme of Charles Misner [31] and the (now almost orthodox) inflationary scenarios. In chaotic cosmology, Misner envisaged viscous forces dissipating any initial anisotropies to yield an isotropic expanding universe with very smooth spatial sections. It was eventually realized that such processes cannot accomplish this, but inflation is now invoked to fulfil this function.

As long as inflation can be initiated, it severely attenuates all initial inhomogeneities and anisotropies, ensuring that the resulting domain is nearly flat, causally connected and smooth on very large scales. At the same time, it preserves the low-amplitude quantum fluctuations of the early universe. These gradually develop into galaxies and clusters of galaxies but within a large-scale, nearly homogeneous background. Although it now appears that inflation is also incapable of rendering our universe insensitive to initial conditions – because the onset of inflation itself seems to require very special initial conditions [32,33] – attempts to realize the Cosmological Indifference Principle persist.

In fact, the multiverse idea may itself be interpreted this way (see ref. [5], p. 285). Taken alone, our universe requires very finely tuned initial conditions. Placing it in a really existing ensemble of other universes or domains

seems, at first sight, to dispense with the need for that fine-tuning. However, as we have seen, they are certainly not uniquely specified. Accounting for the existence and specific character of our multiverse requires an adequate generating process or principle, which must explain the particular distribution function specifying it. This may itself require fine-tuning.

In comparing the two opposing philosophical perspectives represented by the anthropic and indifference principles, McMullin [5] points out that the first inevitably involves mind and teleology (see ref. [5], pp. 259–367). This always threatens to take us beyond the domain of natural science to philosophy and theology. The indifference preference studiously avoids any direct appeal to such influences, relying instead on the dynamics inherent in and emerging from the mass–energy distribution itself [8].

25.8 The SAP and transcendent explanations

We have considered the legitimacy and scientific potential of anthropic arguments and we have come to a number of conclusions about the philosophical reach of the two versions of the SAP. We summarize these in five statements.

- Leaving aside the issue of an ultimate explanation, as long as the selection of initial conditions and the fundamental constants cannot be explained by some physical process or relationship, or rendered indifferent by one, a ‘transcendent’ explanation – one that takes us beyond natural science – is needed *if the Principle of Sufficient Reason continues to hold*.² This may take the form of a divine creative agent or a really existing multiverse.
- If we do have good evidence, and an adequately specific model for, the multiverse to which our own universe belongs, thus providing some explanation for its bio-friendly characteristics, this would not be a complete – let alone an ultimate – explanation. We would still require an explanation for the existence and bio-friendly character of the multiverse itself (bearing in mind that there is no unique prescription for it) and for the process through which it emerged – as well as a philosophically ultimate explanation.
- If we have a final theory which uniquely specifies all the characteristics of our universe, including the initial conditions, we cannot employ the

² The Principle of Sufficient Reason, which many philosophers maintain holds in all circumstances, requires that, for every state of affairs, event or outcome, there is an adequate reason or explanation. If, in some fundamental regime (for example quantum cosmology), this were not the case, then we might be able to forego searching for a further, deeper understanding. I personally do not believe this is the case, but it is a possible philosophical stance.

fine-tuning arguments of the SAP either scientifically or philosophically. There would then be only one way in which our universe could exist consistently. This is very unlikely, but we cannot rule it out at present.

- Even if the previous option applies, it would still not eliminate the need for an ultimate explanation or ‘cause’. Nor would it invalidate philosophical arguments from contingency for the existence of God. (Here again we would be invoking the Principle of Sufficient Reason.)
- If we have a final theory that still allows some ‘play’ in the laws of nature, then a theological answer in terms of intentional action by a divine agent or Creator is certainly acceptable, as long as we are allowing ourselves to go beyond the natural sciences and admit a theological or metaphysical frame of reference. Science can neither support nor exclude such a conclusion. It cannot even adjudicate the question. However, in going beyond the sciences, we must avoid putting God in the ‘scientific gaps’. Perhaps our final theory is not really final! We should ensure that the divine agent is always a primary or ultimate cause – not one that could conceivably be filled by some unknown secondary or created cause [34].

References

- [1] R. H. Dicke. Dirac’s cosmology and Mach’s principle. *Nature*, **192** (1961), 440.
- [2] C. B. Collins and S. W. Hawking. Why is the universe isotropic? *Astrophys. J.* **180** (1973), 317.
- [3] B. Carter. Large number coincidences and the anthropic principle in cosmology. In *Confrontation of Cosmological Theory with Astronomical Data*, ed. M. S. Longair (Dordrecht: Reidel, 1974), pp. 291–298.
- [4] B. Carter. The anthropic principle and its implications for biological evolution. *Phil. Trans. Roy. Soc. Lond. A* **310** (1983), 347.
- [5] E. McMullin. Indifference principle and anthropic principle in cosmology. *Studies Hist. Phil. Sci.* **24** (1993), 359.
- [6] J. D. Barrow and F. J. Tipler. *The Cosmological Anthropic Principle* (Oxford: Oxford University Press, 1986).
- [7] G. F. R. Ellis, U. Kirchner and W. R. Stoeger. Multiverses and physical cosmology. *Mon. Not. Roy. Astron. Soc.* **347** (2003), 921 [astro-ph/0305292v3].
- [8] W. R. Stoeger, G. F. R. Ellis and U. Kirchner. Multiverses and cosmology: Philosophical issues (2004) [astro-ph/0407329v2].
- [9] A. Linde. Chaotic inflation. *Phys. Lett. B* **129** (1983), 177.
- [10] A. Linde. *Particle Physics and Inflationary Cosmology* (Chur: Harwood Academic Publishers, 1990).
- [11] A. Linde. Inflation, quantum cosmology and the anthropic principle. In *Science and Ultimate Reality*, eds. J. D. Barrow, P. C. W. Davies and C. L. Harper (Cambridge: Cambridge University Press, 2004), pp. 426–458 [hep-th/0211048].

- [12] S. Weinberg. The cosmological constant problem. In *Sources and Detection of Dark Matter and Dark Energy in the Universe*, ed. D. Cline (Berlin: Springer-Verlag, 2001) [astro-ph/0005265].
- [13] S. Weinberg. A priori probability distribution of the cosmological constant. *Phys. Rev. D* **61** (2000), 103505 [astro-ph/0002387].
- [14] J. Garriga and A. Vilenkin. Many worlds in one. *Phys. Rev. D* **64** (2001), 043511.
- [15] J. Garriga and A. Vilenkin. A prescription for probabilities in eternal inflation. *Phys. Rev. D* **64** (2001), 0235074 [gr-qc/0102090].
- [16] J. Garriga and A. Vilenkin. Testable anthropic predictions for dark energy. *Phys. Rev. D* **67** (2003), 043503 [astro-ph/0210358].
- [17] S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi. de Sitter vacua in string theory. *Phys. Rev. D* **68** (2003), 046005.
- [18] L. Susskind. This volume (2007) [hep-th/03021219].
- [19] D. Freivogel and L. Susskind. Framework for the string theory landscape. *Phys. Rev. D* **70** (2004), 126007.
- [20] B. Freivogel, M. Kelban, M. R. Martinez and L. Susskind. Observational consequences of a landscape. *JHEP*, **0603** (2006), 039 [hep-th/0505232].
- [21] L. Smolin. *The Life of the Universe* (Oxford: Oxford University Press, 1999).
- [22] M. Tegmark. Parallel Universes, *Sci. Am.* **288** (5) (May 2003), 30.
- [23] C. S. Peirce. In *Collected Papers, Vols. 1–6*, eds. C. Hartstone and P. Weiss (Cambridge MA: Harvard University Press, 1931–1935), vol. 1, para. 65; vol. 5, para. 188.
- [24] C. S. Peirce. In *Collected Papers, Vols. 7 & 8*, ed. A. Burks (Cambridge, MA: Harvard University Press, 1958), vol. 7, paras 202–207; 218–222.
- [25] E. McMullin. *The Inference that Makes Science* (Milwaukee, WI: Marquette University Press, 1992), p. 112.
- [26] E. McMullin. Is philosophy relevant to cosmology? *Am. Phil. Quart.* **18** (1981), 177–189. Reprinted in *Physical Cosmology and Philosophy*, ed. J. Leslie (New York: Macmillan, 1990), pp. 29–50.
- [27] E. McMullin. Truth and explanatory success. In *Proc. Am. Cath. Phil. Assoc.* **59** (1985), 206.
- [28] E. McMullin. Models of scientific inference. *CTNS Bull.* **8** (2) (1988), 1–14.
- [29] P. Allen. *A Philosophical Framework within the Science-Theology Dialogue: A Critical Reflection on the Work of E. McMullin*. Ph.D. dissertation, St. Paul University, Ottawa, 2001, p. 113.
- [30] A. Aguirre. The cold big-bang cosmology as a counter-example to several anthropic arguments. *Phys. Rev. D* **64** (2001), 083508 (astro-ph/0106143).
- [31] C. W. Misner. The isotropy of the universe. *Astrophys. J.* **151** (1968), 431.
- [32] R. Penrose. Difficulties with inflationary cosmology. *Ann. N. Y. Acad. Sci.* **571** (1989), 249.
- [33] G. F. R. Ellis, P. McEwan, W. R. Stoeger and P. Dunsby. Causality in inflationary universes with positive spatial curvature. *Gen. Rel. Grav.* **34** (2002), 1461.
- [34] W. R. Stoeger. Describing God’s action in the world in light of scientific knowledge of reality. In *Chaos and Complexity: Scientific Perspectives on Divine Action*, eds. R. J. Russell, N. Murphy and A. R. Peacocke (Rome: Vatican Observatory Publications and the Center for Theology and the Natural Science, 1995), pp. 239–261.

The multiverse hypothesis: a theistic perspective

Robin Collins

Department of Philosophy, Messiah College

26.1 Introduction

In articles published in physics journals, the multiverse hypothesis is strictly regarded from a non-theistic perspective, as a possible explanatory hypothesis for the life-permitting values of the constants of physics. Further, there have been several attempts to make specific predictions with regard to the values of these constants from a multiverse hypothesis, such as the value of the cosmological constant [1–3]. Such approaches reflect the legitimate methodological naturalism of physics. However, in wider-ranging philosophical discussions of the multiverse hypothesis – as found in various books on the topic – the issue arises as to what is the relation between the multiverse hypothesis and much larger philosophical issues, particularly whether reality is ultimately impersonal or personal in nature. In such contexts, the multiverse hypothesis is often presented as *the* atheistic alternative to a theistic explanation – such as that offered by John Polkinghorne [4] – of the purported fine-tuning of the cosmos for intelligent life. In this contribution, I will attempt to explain why, contrary to the impression one often gets, contemporary physics and cosmology are not only compatible with theism, but could arguably be thought to suggest a theistic explanation of the Universe or multiverse. I do not expect necessarily to convince anyone of the theistic point of view, realizing that many factors – both theoretical and personal – underlie our views of the ultimate nature of reality. Further, since there is no contribution to this collection arguing for an atheistic point of view, I will attempt to give voice – and replies – to some of the significant concerns and objections of non-theists.

26.2 Terminology: God and multiple universes

First, we need to clarify what we mean by theism and the multiverse hypothesis. With regard to theism, I take the theistic hypothesis to be the

Universe or Multiverse?, ed. Bernard Carr. Published by Cambridge University Press.
© Cambridge University Press 2007.

claim that an omnipotent and omniscient being is ultimately responsible for the existence of the Universe. The concept of God I will assume is the standard so-called Anselmian one, according to which God is defined as the greatest possible being, but this is not essential to my argument. It is often claimed that this conception of God is central to all of the world's theistic religious traditions – Islam, Judaism, Christianity and theistic versions of Hinduism. As an alternative to the Anselmian conception, one could simply think of the God hypothesis as the minimal one needed to explain the existence of the Universe via some sort of intelligent agent; that is, the hypothesis that there exists some highly intelligent and very powerful, and at least partly transcendent, agent that is ultimately responsible for the existence of the Universe.

Second, we need to be clear on what we mean by the multiverse hypothesis. There are essentially two kinds of multiverse hypotheses: what could be called the *physical* or *universe-generator* version and the *metaphysical* version. In the universe-generator version, some particular real physical process – such as an inflaton field – is postulated that generates the many universes (or domains), whereas in the metaphysical version the universes are thought to exist on their own, without being generated by any physical process.¹ In this chapter, I will primarily restrict myself to discussing the physical version, but the arguments in Section 26.7 on the beauty of the laws of nature apply to both versions.

26.3 The compatibility between theism and the multiverse hypothesis

In this section, I will argue not only that theism is compatible with the universe-generator version of the multiverse hypothesis, but also that theists might even have reasons for preferring a multiverse over a single universe. Since within the world's theistic traditions, God is considered infinite and infinitely creative, it makes sense that creation would reflect these attributes, and hence that physical reality might be much larger than one universe. Further, it makes sense that an infinitely creative God might create these many universes via some sort of universe-generator, since arguably this would be somewhat more elegant and ingenious than just creating them *ex nihilo*. Nonetheless, the idea that the Universe is infinite, or that there is some multiverse, has not been stressed in Western theology. A large part

¹ I define a 'universe' as any region of spacetime that is disconnected from other regions in such a way that the parameters of physics in that region could differ significantly from what they are in other regions. The typical form of the metaphysical multiverse hypothesis is the claim that all possible mathematical structures are actual [5] or that all possible realities exist [6].

of the reason for this seems to be historical and not intrinsic to the Western theistic conception of God. The highly influential late medieval theology, for instance, was self-consciously based on Aristotelean metaphysics. For Aristotle, however, space was defined in terms of the extension enclosed by a physical object – such as the medieval crystalline spheres in the case of our universe – which were conceived of as necessarily finite. Indeed, many felt that restricting God to creating one universe was contrary to the omnipotence of God. Only with the eventual questioning of Aristotle by thinkers such as Nicholas of Cusa and, later, Giordano Bruno did the positive suggestion emerge that space was infinite, with perhaps an infinity of worlds. Although Bruno was considered a heretic by the Roman Catholic Church at the time for a variety of reasons, he spoke for many theistic thinkers when he declared [7]:

Thus is the excellence of God magnified and the greatness of his kingdom made manifest; he is glorified not in one, but in countless suns; not in a single earth, but in a thousand, I say, in an infinity of worlds.

This belief in a plurality of worlds, many of which are inhabited, was further developed and elaborated by Isaac Newton and many of his contemporaries, such as Gottfried Leibnitz. As Michael Crowe [8] notes, by 1750 belief in the plurality of worlds ‘had been championed by an array of authors, including some of the most prominent of the age’.²

Indeed, the fact that the multiverse scenario fits well with an idea of an infinitely creative God, and that so many factors in contemporary cosmology and particle physics conspire together to make an inflationary multiverse scenario viable, should give theists good reason to consider a theistic version of it. Added to these reasons is the fact that science has progressively shown that the visible part of the Universe is vastly larger than we once thought, with a current estimate of some 300 billion galaxies with 300 billion stars per galaxy. Thus, it makes sense that this trend will continue and physical reality will be found to be much larger than a single universe.

Of course, one might object that creating a fine-tuned universe by means of a universe-generator would be an inefficient way for God to proceed. But this assumes that God does not have some motive for creation – such as that of expressing His/Her infinite creativity and ingenuity – other than creating a life-permitting cosmos using the least amount of material. But why would one make this assumption unless one already had a pre-existing model of God as something more like a great engineer instead of a great

² A more contemporary Christian writer who has imaginatively developed this theme is the late C. S. Lewis in his fantasy series *Chronicles of Narnia*, in which God is imagined to have created a large number of different realms of being.

artist? Further, an engineer with infinite power and materials available would not necessarily care much about efficiency.

26.4 Understanding the fine-tuning

Our next question is this: Does the multiverse hypothesis undercut the case for some sort of design from fine-tuning, as advocated by various thinkers [9]? I will argue that, at most, it mitigates the case by rendering it less quantitative. First, however, we will need to sketch the fine-tuning argument itself.

Fine-tuning has been widely claimed to provide evidence of, or at least suggest, some sort of divine design of the Universe. Elsewhere, I have attempted to develop this argument in a more principled way [10]. As I develop it, the ‘core version’ of the argument essentially involves claiming that the existence of intelligent-life-permitting values for the constants of physics is not surprising under theism, but highly surprising under the non-design, non-multiverse hypothesis – that is, the hypothesis that there is only a single universe and that it exists as a brute fact without any further explanation. Further, the reason it seems highly surprising under the non-design, non-multiverse hypothesis is that, for certain constants of physics, the range of intelligent life-permitting values is purportedly small compared with some non-arbitrarily defined comparison range – such as the range of force strengths in nature when discussing the fine-tuning of gravity and other forces.

Using what could be called the ‘surprise principle’, it follows that the existence of intelligent-life-permitting values for the constants provides evidence in favour of theism over the non-design, non-multiverse hypothesis.³ Note that no claim is being made here that theism is the best explanation of the constants being intelligent-life-permitting. To judge that a hypothesis is the best explanation of a body of data involves an overall assessment of the hypothesis, not simply how well it explains the particular data in

³ The surprise principle can be stated as follows. Let H1 and H2 be two competing non-*ad-hoc* hypotheses; that is, hypotheses that were not constructed merely to account for the data E in question. According to the surprise principle, if a body of data E is less surprising under hypotheses H1 than H2, then the data E provides evidence in favour of H1 over H2. The best way, I believe, of explicating what the notion of surprise is here is in terms of what philosophers call *conditional epistemic probability*, in which case the above principle becomes a version of the *likelihood principle* or the *principle of relevance*, which is a standard principle of probabilistic confirmation theory (see, e.g., ref. [11]). Unlike what D. H. Mellor [12] assumes in his objection to Martin Rees’s claim that cosmic fine-tuning supports the multiverse hypothesis, conditional epistemic probability is not a measure of ignorance. Rather, it has to do with relations of support or justification between propositions. As John Maynard Keynes stated in his treatise on probability [13], ‘if a knowledge of *h* justifies a rational belief in *a* of degree α , we say that there is a ‘probability-relation’ of degree α between *a* and *h*’. Although I think Keynes’s account needs further work, I believe it is on the right track. For a recent development of this notion of conditional epistemic probability, see ref. [14].

question. The fact that Johnny's fingerprints are on the murder weapon might significantly support the claim that Johnny committed the murder. Nonetheless, Johnny's committing the murder might not be the best explanation of the fingerprints, since we might have strong, countervailing evidence that he did not commit the murder. Perhaps, for instance, five reliable witnesses saw Johnny at a party at the time of the murder. Similarly, all I claim is that the evidence of fine-tuning supports theism over the non-design, non-multiverse hypothesis. However, to judge whether we should infer that theism is the best explanation of the structure of the Universe – versus simply accepting the Universe as a brute given – involves many factors beyond the evidence of fine-tuning.

One of the key claims in the above argument is that the existence of a universe with intelligent-life-permitting cosmic conditions is not surprising under theism. This claim needs support instead of merely being assumed in an *ad hoc* way. Essentially, the argument is that if God is good – an assumption that is part of classical theism – then it is not surprising that God would create a world with intelligent beings, because the existence of such beings has positive value, at least under the theistic hypothesis.

Philosophers of religion offer a variety of justifications for the claim that God is perfectly good, or at least why ascribing goodness to God is not arbitrary. Here I will simply present two. First, some philosophers appeal to the Anselmian conception of God mentioned above, arguing that a being that is perfectly good is greater than one that is not perfectly good, and hence the characteristic of perfect goodness should be ascribed to God. Second, other philosophers – such as Richard Swinburne [15] – argue that, once grasped, the goodness or beauty of a state of affairs gives any conscious agent a reason to prefer that state of affairs. The idea is that part of grasping that a state of affairs has value – whether moral or aesthetic – is to 'feel' the desirability of the state, and hence have some motivation to bring it about. Under this view, for instance, people only do evil either because they do not grasp the disvalue of doing evil, or because some other influence tempts them to do what they recognize as having ethical disvalue. Since God is perfectly free – that is, God is not subject to countervailing desires in the way we are – God would have no motive to act against the good or beautiful. So, we would naturally expect God to act to bring about states of beauty and goodness. Whether one buys this sort of argument or not, I think that at minimum one has to admit that it is in no way arbitrary or *ad hoc* to hold that God has the desire to bring about states of goodness and beauty.

If this is right, then theism provides a natural connection between the moral and aesthetic realms of value and any such value we might have reason

to believe that the Universe is structured to realize. One need not necessarily invoke a personal God to provide this connection, however. John Leslie [16], for instance, proposes what he calls a ‘neo-Platonic principle of ethical requiredness’, as suggested by Book VI of Plato’s *Republic*, which could be thought of as a ‘God substitute’. According to this principle, what ought to exist does exist. Further, Leslie claims, this principle exists as a matter of metaphysical necessity, much as many philosophers view the truths of mathematics, such as $2 + 2 = 4$. Thus its existence is self-explanatory. Leslie points out, however, that his neo-Platonic principle is compatible with theism, and might even entail theism: since God is a being of supreme value, one could argue that the principle entails that God would exist. Thus, even if we adopt Leslie’s hypothesis, this would not necessarily provide an alternative to the theistic explanation of the fine-tuning of the Universe.⁴

26.5 Multiverse-generator needs design

In this section, I will argue that – even if a multiverse-generator exists – the argument for theism from the fine-tuning of the constants for intelligent life is not completely eliminated. The argument essentially goes as follows. The multiverse-generator itself, whether of the inflationary variety or some other type, seems to need to be ‘well designed’ in order to produce life-sustaining universes. After all, even a mundane item like a bread machine, which only produces loaves of bread instead of universes, must be well designed as an appliance and must have the right ingredients (flour, water and yeast) to produce decent loaves of bread. If this is right, then invoking some sort of multiverse-generator as an explanation of the fine-tuning serves to kick the issue of design up one level, to the question of who designed the multiverse-generator.

The inflationary multiverse scenario, widely considered as the most physically viable, provides a good test case of this line of reasoning. The inflationary multiverse-generator can only produce life-sustaining universes (or regions of spacetime) because it has the following ‘components’ or ‘mechanisms’:

- (1) *A mechanism to supply the energy needed for the bubble universes.* This mechanism is the hypothesized inflaton field. By imparting a constant

⁴ It should be noted, however, that in Leslie’s recent book [17] he argues for a pantheistic conception of God based on this principle and other considerations. In his view, every universe (or reality) whose sum value (both moral and aesthetic) is positive exists as a thought in the mind of God, with our universe itself existing as one such thought. (Like models in a computer simulation, God’s thoughts are considered to have substantial structure – and thus substantial existence – in God’s mind.) For a short critique of this fascinating book and Leslie’s response, see my review essay [18] and ref. [19].

energy density to empty space as space expands, the inflaton field can act ‘as a reservoir of unlimited energy’ [20] for the bubbles.

- (2) *A mechanism to form the bubbles.* This mechanism relates to Einstein’s equations of general relativity. Because of their peculiar form, Einstein’s equations dictate that space expands at an enormous rate in the presence of a field – like the inflaton – which imparts a constant (and homogeneous) energy density to empty space. This causes both the formation of the bubble universes and the rapid expansion which keeps them from colliding.
- (3) *A mechanism to convert the energy of the inflaton field to the normal mass/energy we find in our universe.* This mechanism is Einstein’s equivalence of mass and energy, combined with an hypothesized coupling between the inflaton field and normal mass/energy fields we find in our universe.
- (4) *A mechanism that allows enough variation in constants of physics among universes.* Currently, the most physically viable candidate for this mechanism is superstring or M-theory. Superstring theory might allow enough variation in the constants of physics among bubble universes to make it reasonably likely that a fine-tuned universe would be produced, but no one knows for sure.⁵

Without all these ‘components’, the multiverse-generator would almost certainly fail to produce a single life-sustaining universe. If, for example, the universe obeyed Newton’s theory of gravity instead of Einstein’s, the vacuum energy of the inflaton field would at best create a gravitational attraction causing space to contract rather than expand.

In addition to the four factors listed above, the inflationary multiverse generator can only produce life-sustaining universes because the right background laws are in place. Specifically, the background laws must be such as to allow the conversion of the mass/energy into the material forms required for the sort of stable complexity needed for life. For example, without the principle of quantization, all electrons would be sucked into the atomic nuclei and hence atoms would be impossible; without the Pauli exclusion principle, electrons would occupy the lowest atomic orbit and hence complex and

⁵ See Leonard Susskind’s contribution to this volume [21] for the variations allowed by superstring theory. The other leading alternatives to string theory being explored by physicists, such as the currently proposed models for Grand Unified Theories (GUTs), do not appear to allow for enough variation. The simplest and most studied GUT, $SU(5)$, allows for three differing sets of values for the fundamental constants of physics when the other non- $SU(5)$ Higgs fields are neglected [22]. Including all the other Higgs fields, the number of variations increases to perhaps several dozen [23]. Merely to account for the fine-tuning of the cosmological constant, however, which is estimated to be fine-tuned to be at least one part in 10^{53} , would require on the order of 10^{53} variations of the physical constants among universes.

varied atoms would be impossible; without a universally attractive force between all masses, such as gravity, matter would not be able to form sufficiently large material bodies (such as planets) for complex, intelligent life to develop or for long-lived stable energy sources like stars to exist.⁶

In sum, even if an inflationary multiverse-generator exists, it must involve just the right combination of laws, principles and fields for the production of life-permitting universes; if one of the components were missing or different – such as Einstein’s equation or Pauli’s exclusion principle – it is unlikely that any life-permitting universes could be produced. In the absence of alternative explanations, it follows from the surprise principle that the existence of such a system could be considered to suggest design since it seems very surprising that such a system would have just the right components as a brute fact, but not surprising under the theistic design hypothesis. Thus, it does not seem that one can completely escape the suggestion of design merely by hypothesizing some sort of multiverse-generator.

It must be admitted, however, that if such a multiverse-generator could be verified, the sort of *quantitative* evidence for design based on the fine-tuning of the constants would be eliminated. Whereas the degree of fine-tuning of a particular constant of physics could arguably be assigned a number – such as that corresponding to the ratio of the length of its intelligent-life-permitting range to some non-arbitrarily specified ‘theoretically possible’ range – we cannot provide a quantitative estimate for the degree of apparent design in the cases mentioned above. All we can say is that if certain seemingly highly specific sorts of laws were not in place, no life-sustaining universes could be generated. Thus, depending on the weight one attaches to such quantitative estimates, the evidence for design would be mitigated, although not completely eliminated.

26.6 Multiverses, design and the beauty of the laws of nature

Next, I want to look at what many consider another powerful suggestion of design from modern physics, that arising from the ‘beauty’ and ‘elegance’ of the laws of nature. This suggestion of design bypasses the multiverse objection to the design argument, whether the multiverse hypothesis is of

6 Although some of the laws of physics can vary from universe to universe in string theory, these background laws and principles are a result of the structure of string theory and therefore cannot be explained by the inflationary/superstring multiverse hypothesis since they must occur in all universes. Further, since the variation among universes would consist of variation of the masses and types of particles, and the form of the forces between them, complex structures would almost certainly be atom-like, and stable energy sources would almost certainly require aggregates of matter. Thus, the above background laws seem necessary for there to be complex, embodied intelligent observers in any of the many universes generated in this scenario, not merely a universe with our specific types of particles and forces.

the universe-generator or metaphysical variety. The idea that the laws of nature are beautiful and elegant is commonplace in physics, with entire books devoted to the topic. Indeed, Steven Weinberg – who is no friend of theism – devotes an entire chapter of his book *Dreams of a Final Theory* [24] to beauty as a guiding principle in physics. As Weinberg notes, ‘mathematical structures that confessedly are developed by mathematicians because they seek a sort of beauty are often found later to be extraordinarily valuable by physicists’ (see p. 153 of ref. [24]). To develop our argument, however, we need first to address what is meant by beauty. As Weinberg notes, the sort of beauty exemplified by physics is that akin to classical Greek architecture. The highpoint of the classical conception of beauty could be thought of as that of William Hogarth in his 1753 classic *The Analysis of Beauty* [25]. According to Hogarth, simplicity with variety is the defining feature of beauty or elegance, as illustrated by a line drawn around a cone. He went on to claim that simplicity apart from variety, as illustrated by a straight line, is boring rather than elegant or beautiful.

The laws of nature seem to manifest just this sort of simplicity with variety: we inhabit a world that could be characterized as having fundamental simplicity that gives rise to the enormous complexity needed for intelligent life. To see this more clearly, we will need to explicate briefly the character of physical law, as discovered by modern physics. I will do this in terms of various levels.

The physical world can be thought of as ordered into the following, somewhat overlapping, levels. Level 1 consists of observable phenomena. The observable world seems to be a mixture of order and chaos: there is regularity, such as the seasons or the alternation of day and night, but also many unique, unrepeatable events that do not appear to fall into any pattern. Level 2 consists of postulated patterns that exist among the observable phenomena, such as Boyle’s law of gases. The formulation of level 2 marks the beginning of science as understood in a broad sense. Level 3 consists of a set of postulated underlying entities and processes hypothesized to obey some fundamental physical laws. Such laws might be further explained by deeper processes and laws, but these will also be considered to inhabit level 3. So, for instance, both Newton’s law of gravity and Einstein’s equations of General Relativity would be considered to be level 3. The laws at level 3, along with a set of initial (or boundary) conditions, are often taken to be sufficient to account for the large-scale structure of the Universe.

Level 4 consists of fundamental principles of physics. Examples of this are the principle of the conservation of energy and the gauge principle (that is, the principle of local phase invariance), the principle of least action,

the anti-commutation rules for fermions (which undergird Pauli's exclusion principle) and the correspondence principle of quantum mechanics (which often allows one to write the quantum mechanical equations for a system by substituting quantum operators for certain corresponding variables into a classical equation for the system). These are regulative principles that, when combined with other principles (such as choosing the simplest Lagrangian), are assumed to place tight constraints on the form that the laws of nature can take in the relevant domain. Thus, they often serve as guides to constructing the dynamical equations in a certain domain.

The laws at level 3 and the principles of level 4 are almost entirely cast in terms of mathematical relations. One of the great achievements of science has been the discovery that a deeper order in observable phenomena can be found in mathematics. As has been often pointed out, the pioneers of this achievement – such as Galileo, Kepler, Newton and Einstein – had a tremendous faith in the existence of a mathematical design to nature, although it is well known that Einstein did not think of this in theistic terms but in terms of a general principle of rationality and harmony underlying the Universe. As Morris Kline, one of the most prominent historians of mathematics, points out [26]:

From the time of the Pythagoreans, practically all asserted that nature was designed mathematically... During the time that this doctrine held sway, which was until the latter part of the nineteenth century, the search for mathematical design was identified with the search for truth.

Level 5 consists of the basic mathematical structure of current physics, for example the mathematical framework of quantum mechanics, though there is no clear separation between much of level 5 and level 4. Finally, one might even want to invoke a level 6, which consists of the highest-level guiding metaphysical principles of modern physics – for example, that we should prefer simple laws over complex laws, or that we should seek elegant mathematical explanations for phenomena.

Simplicity with variety is illustrated at all the above levels, except perhaps level 6. For example, although observable phenomena have an incredible variety and much apparent chaos, they can be organized via relatively few simple laws governing postulated unobservable processes and entities. What is more amazing, however, is that these simple laws can in turn be organized under a few higher-level principles (level 4) and form part of a simple and elegant mathematical framework (level 5).

One way of thinking about the way in which the laws fall under these higher-level principles is as a sort of fine-tuning. If one imagines a space of

all possible laws, the set of laws and physical phenomena we have are just those that meet the higher-level principles. Of course, in analogy to the case of the fine-tuning of the parameters of physics, there are bound to be other sets of laws that meet some other relatively simple set of higher-level principles. But this does not take away from the fine-tuning of the laws, or the case for design, any more than the fact that there are many possible elegant architectural plans for constructing a house takes away from the design of a particular house. What is important is that the vast majority of variations of these laws end up causing a violation of one of these higher-level principles, as Einstein noted about general relativity. Further, it seems that, in the vast majority of such cases, such variations do not result in new, equally simple higher-level principles being satisfied. It follows, therefore, that these variations almost universally lead to a less elegant and simple set of higher-level physical principles being met. Thus, in terms of the simplicity and elegance of the higher-level principles that are satisfied, our laws of nature appear to be a tiny island surrounded by a vast sea of possible law structures that would produce a far less elegant and simple physics.

As testimony to the above point, consider what Steven Weinberg and other physicists have called the ‘inevitability’ of the laws of nature (see, e.g., pp. 135–153 and 235–237 of ref. [24]). The inevitability that Weinberg refers to is not the inevitability of logical necessity, but rather the contingent requirement that the laws of nature in some specified domain obey certain general principles. The reason Weinberg refers to this as the ‘inevitability’ of the laws of nature is that the requirement that these principles be met often severely restricts the possible mathematical forms the laws of nature can take, thus rendering them in some sense inevitable. If we varied the laws by a little bit, these higher-level principles would be violated.

This inevitability of the laws is particularly evident in Einstein’s general theory of relativity. As Weinberg notes, ‘once you know the general physical principles adopted by Einstein, you understand that there is no other significantly different theory of gravitation to which Einstein could have been led’ (p. 135 of ref. [24]). As Einstein himself said, ‘To modify it [general relativity] without destroying the whole structure seems to be impossible.’

This inevitability, or near-inevitability, is also illustrated by the gauge principle, the requirement that the dynamical equations expressing the fundamental interactions of nature – the gravitational, strong, weak and electromagnetic forces – be invariant under the appropriate local phase transformation. When combined with the heuristic of choosing the simplest interaction Lagrangian that meets the gauge principle and certain other background constraints, this has served as a powerful guide in constructing

the equations governing the forces of nature (e.g. the equations for the forces between quarks). Yet, as Ian Atchison and Anthony Hey point out, there is no compelling logical reason why this principle must hold. Rather, they claim, this principle has been almost universally adopted as a fundamental principle in elementary particle physicists because it is ‘so simple, beautiful and powerful (and apparently successful)’ [27]. Further, as Alan Guth points out [28], the original ‘construction of these [gauge] theories was motivated mainly by their mathematical elegance’. Thus, the gauge principle provides a good example of a contingent principle of great simplicity and elegance that encompasses a wide range of phenomena, namely the interactions between all the particles in the Universe.

26.7 Potential non-theistic explanations of beauty and elegance

Theism offers a natural, non-*ad-hoc*, explanation of why the laws of nature can be encompassed by such higher-level principles. As mentioned above, it has been part of traditional theism that God would be motivated to bring about an aesthetically pleasing universe. Can a non-theistic, non-design view of reality offer an explanation? One reaction to this purported need for a theistic explanation might be to claim that it is no more surprising that such higher-level principles exist than that nature has simple laws. Further, it could be argued that, just as simple laws (along with the initial conditions) determine the various phenomena of nature, so the higher-level principles determine which laws of nature exist. Given that we take the higher-level principles as ontologically primary, it is therefore no surprise that the lower-level laws fall under them; once such principles are given, everything else follows. Accordingly, the only things that could be surprising are that the higher-level principles are mathematically simple or that they exist at all. But why should these be surprising?

One flaw in the above argument is that it does not seem that one can plausibly think of these principles as in themselves having any causal power to dictate the lower-level phenomena or laws. It is easy to be misled at this point, however, into thinking that they do. Because we can often derive (with a few additional assumptions) the lower-level laws from the higher-level principle, it is easy to think that somehow these higher-level principles make the lower-level laws what they are. Rather, the causation or dependence is in the other direction: it is because the laws and phenomena are what they are that these principles hold universally, not the other way around. The principles are therefore not ontologically primary.

An analogy from architecture might help to illustrate this point: insofar as the placement of windows in a building follows higher-level principles, it is not because the principles in themselves have a special power to make the windows have the right positions. Rather, it is because of the position of the windows that the higher-level principles hold. Further, insofar as the higher-level principles could be said to have a causal efficacy to determine the placement of the windows, it is only via the causal powers of intelligent agents, such as the people who constructed the building.

One reason for claiming that these principles have no intrinsic causal powers is that – except for being an intention or thought in some mind, human or transcendent – it is difficult to see how these higher-level principles could be anything over and above the patterns into which the laws and phenomena of nature fall. For example, they do not appear to be reducible to the causal powers of actual entities, as some philosophers claim about the laws of nature.⁷ Instead, insofar as entities possess causal powers, the principles describe the arrangement of the causal powers of a diverse class of such entities – for example the fundamental particles – and therefore cannot be the powers of any given entity. And even if this arrangement were the result of the causal power of some single type of entity – for example a superstring – it would still be surprising that the arrangement could be captured and unified by a few simple higher-level mathematical rules. This is analogous to the claim that, even if the fine-tuning of the constants of physics for life were to be explained by some Grand Unified Theory, it would still be amazing that the theory that happened to exist was one that yielded values for the constants that were intelligent-life-permitting.

One could still insist that there is no reason to think that it is surprising that individual laws collectively fall under simple and elegant mathematical rules which are, in turn, expressible in an elegant and incredibly fruitful system of mathematics, such as the complex numbers in the case of quantum mechanics. Perhaps one could argue at this point that it is just an unexplainable fact about the world, and that all explanations must come to an end at some point. Invoking God, it could be argued, merely moves the problem up one level: the theist is still left with postulating the existence of God as an unexplained given. Here the debate can take an even more philosophical turn – with the theist offering reasons for why God is a superior stopping point for explanation and the atheist denying those reasons. All we will say here is that given that theism makes more sense of the existence of

⁷ See, for example, the book by Rom Harré and Edward Madden [29]. Under the conception of laws as expressing causal powers, Einstein's equation of general relativity would be seen as being grounded in the causal powers of matter to bend spacetime.

this fine-tuning for beauty and elegance than atheism, it offers us a reason for believing in theism.

Further, this ‘fine-tuning’ for simplicity and elegance cannot be explained either by the universe-generator or metaphysical multiverse hypothesis, since there is no reason to think that intelligent life could only arise in a universe with simple, elegant underlying physical principles. Certainly, a somewhat orderly macroscopic world is necessary for intelligent life, but there is no reason to think that this requires a simple and elegant underlying set of physical principles. This is especially clear when one considers how radically different the framework and laws of general relativity and quantum mechanics are from the world of ordinary experience: although the regularities of the everyday world are probably derived from the underlying laws of quantum mechanics and general relativity, they do not reflect the structure of those laws. Indeed, it is this difference in structure between the classical, macroscopic world and the quantum world that has largely given rise to the interpretive problems of quantum mechanics. Thus, there is little reason based on an observation selection effect to expect the sort of macroscopic order necessary for intelligent life to be present in the underlying, microscopic world.

Another alternative is to attempt to explain the simplicity of the world by some sort of metaphysical principle, according to which the world is more likely to be simple than complex. One problem with this view is that there are many, many simpler possible worlds than ours, such as one with a single particle that simply travels in a straight line. The enormous actual complexity of our world thus strongly testifies against this claim.

One way of getting around this problem is to combine this metaphysical principle of simplicity with a metaphysical many-universe hypothesis, according to which all possible mathematical structures are instantiated in some universe or another. One such view is suggested by Max Tegmark [30]. Using this hypothesis, one could explain the actual complexity of the Universe by claiming that only sufficiently complex universes could contain embodied observers, whereas the simplicity of the world would be explained by claiming that simple worlds are given a higher probabilistic weight than complex worlds. As Tegmark suggests, ‘One could reward simplicity by weighting each mathematical structure by 2^{-n} , where n is the algorithmic information content measured in bits, defined as the length of the shortest bit string . . . that would specify it’ (see p. 16 of ref. [30]).

Even granting the many-universe hypothesis, however, such a metaphysical principle runs into severe problems. For one thing, simplicity seems to be conceptual-framework relative and so it is difficult to see how there

could be any such metaphysical principle. Any mathematical equation, for instance, can be written in a simple form given that one constructs the right mathematical properties. For example, consider the equation $Y = 2x + 4x^2 + 7.1x^5$. Define $F(x)$ by the expression on the right-hand side of the equation. Given that the concept of a function $F(x)$ is part of our mathematical repertory, we can write the above equation as $Y = F(x)$, which is much simpler than our original way of expressing Y . The only way I can see around this problem is to postulate a set of primitive mathematical properties and then define complexity in terms of the shortest bit string that would specify the mathematical equation using only those primitive properties. Without such a postulate, simplicity will be relative to the repertory of mathematical properties with which one has to work. An example of this viewpoint-dependence occurs when Newton's law of gravity is translated into the framework of general relativity and vice versa. When this is done, however, their respective simplicity vanishes. As Misner, Thorne and Wheeler point out, expressed in the conceptual framework of general relativity, Newton's gravitational law is extremely complex. On the other hand, if expressed in the Newtonian framework, 'Einstein's field equations (ten of them now!) are horrendously complex' [31]. So the respective simplicity of each is dependent on the conceptual framework in which it is written.

Other problems plague this appeal to a principle of simplicity. For example, the Universe appears to be infinitely complex when one takes into account the complexity of the initial conditions – such as the initial continuous distribution of mass/energy at some chosen surface of constant proper time. Such a distribution would be continuous, and so would take a non-denumerably infinite amount of information to specify. So one's metaphysical principle of simplicity would have to be much more restrictive, such as dictating that some global feature – such as the way the distribution of mass/energy develops with time – can be described using a simple rule, which makes it even less plausible.

Even breaking it into initial conditions plus development in time is metaphysically arbitrary, however, since it is well known that in general relativity there is no single way of deciding which sets of space-like separated points will count as hypersurfaces of constant time. On the other hand, even if there were a preferred set of hypersurfaces – such as that corresponding to those hypersurfaces yielding the same proper time for each element of the cosmic fluid – the temporal development of the mass/energy is describable by many different mathematical systems of equations, as pointed out above. For example, since the quantity of mass/energy at any spacetime point is given

by a real number, the complete temporal development of the mass/energy with time is given by an exceedingly complex function over the real numbers that maps mass/energy distributions (or probabilities of such distributions) from some arbitrarily chosen initial hypersurface to all future hypersurfaces. So the ‘manifest’ temporal development of mass/energy is actually exceedingly complex, at least as expressed in terms of mathematical terms we normally treat as basic.

What is amazing is that, presumably, this mass/energy distribution can be reconstructed using a relatively few simple rules expressed within the complex numbers – that is, the rules of some quantum mechanical theory, such as a (yet undeveloped) theory of quantum gravity. So, the principle of simplicity would require that the weight we attach to a type of universe – that is, what proportion of the space of universes be encompassed by this type – should not be determined by the degree of complexity of the mathematical system a type of universe exemplifies since it exemplifies multiple systems. Rather, it would need to be determined by the simplest mathematical framework in terms of which its temporal development can be expressed. Given all these complications, such a principle seems to lose almost any intuitive appeal.⁸

The alternative to such a mind-independent principle of simplicity, with all its metaphysical baggage, is to claim that simplicity in physics is relative to both our conceptual framework (instead of some primitive set of mathematical properties) and to our way of breaking up the elements of physical reality (e.g. into laws and initial conditions). According to theism, our minds and the world ultimately owe their origin to God, so it makes sense that the Universe would – at some deep level – be reflective of the preferences of the human mind. Thus, the dependence of simplicity and elegance on our conceptual framework does not present a problem for the theist. However, this partially anthropomorphic characterization of simplicity, as occurs in physics, does not fit well with a mind-independent principle of simplicity

⁸ Since within the metaphysical multiverse hypothesis there will exist worlds that have local islands of order that contain conscious observers, but are otherwise extremely chaotic, the only way to have an expectation for what our universe should look like is to consider ourselves to be generic observers. This raises perhaps the most serious objection to Tegmark’s proposal: saying that a certain type of world has a measure X in our space of all possible mathematical structures cannot explain anything, or lead to any sort of predictions, unless that measure is tied to what we, considered as generic observers, should rationally expect. But mathematical measures themselves do not generate expectations; one can put an infinite number of different measures over a space, but clearly all of them could not imply an expectation. In order for a measure to have any significance, one must have some well justified connection between that measure and our expectations. I see no way of establishing such a connection, especially with the odd type of principle of weighting that would actually be required, as elaborated above.

that determines the weight given to various universes – or more precisely, sets of universes – as Tegmark proposes.

Another non-theistic response to this apparent fine-tuning for beauty and elegance of the laws of nature is that the idea of beauty is purely subjective, simply the result of our reading into nature anthropomorphic patterns, in the same way as humans have read meaningful patterns – such as the Bear or the Big Dipper – into the random pattern of stars in the night sky. The major problem with this explanation is that it does not account for the surprising success of the criterion of beauty in the physical sciences. We would not expect patterns that are merely subjective to serve as a basis for theories that make highly accurate predictions, such as the successful prediction of quantum electrodynamics – to nine significant figures – of the quantum correction to the gyromagnetic ratio of the electron. Merely subjectively reading a pattern into an otherwise random pattern is predictively useless. The second problem is that there are significant objective aspects of beauty, at least in the classical sense of beauty, that one can clearly demonstrate in the realm of physics (e.g. symmetry).⁹

A second way of discounting the significance of the apparent beauty of the laws of nature, suggested by Steven Weinberg (see p. 158 of ref. [24]), is that after the scientific revolution scientists unconsciously modified their criteria of beauty to fit nature. The problem with this explanation is that we can point to objective features of the underlying world – its symmetry, its simplicity in variety, its inevitability – that clearly fit the general criteria of the so-called *classical* conception of beauty exemplified in Greek architecture. This is a category of great human significance that originated long before the scientific revolution. Further, the mere fact that scientists use the term ‘beautiful’ instead of some other category to describe the underlying order indicates that they sense a deep congruence between the order of nature and those features normally associated with beauty in other, non-scientific contexts. It is this congruence that Weinberg’s evolutionary explanation fails to explain. Of course, evolution could account for why we have the category of beauty – namely, that it was of survival value. But it cannot account for why a category that has often been considered to have transcendent, even religious, value fits the underlying mathematical order of nature which is so far removed from the order of everyday life where selection pressures played a role. From an evolutionary perspective, the outstanding question

⁹ This is not to say, however, that the Universe exemplifies elegant and simple laws apart from some preferred categorization scheme; rather, as argued above, the concept of the laws of nature being beautiful seems partly dependent on non-arbitrary, intersubjectively shared human conceptual categories.

still remains as to why a category selected for survival value – for example, because it helped attract mates – would serve as such a useful guide to the underlying order of nature.

Finally, the form of argument in this case for design has the same form as that in the case of the fine-tuning of the constants for intelligent life, except that this fine-tuning cannot be explained by the multiverse hypothesis. One way of putting the argument is in terms of the ‘surprise principle’ we invoked in the argument for the fine-tuning of the constants for the emergence of intelligent life. Specifically, as applied to this case, one could argue that the fact that the phenomena and laws of physics are fine-tuned for simplicity with variety is highly surprising under the non-design hypothesis, but not highly surprising under theism. Thus, the existence of such fine-tuned laws provides significant evidence for theism over the non-design hypothesis. Another way one could explicate this argument is as follows. Atheism seems to offer no explanation for the apparent fine-tuning of the laws of nature for beauty and elegance (or simplicity with variety). Theism, on the other hand, seems to offer such a natural explanation: for example, given the classical theistic conception of God as the greatest possible being, and hence a being with a perfect aesthetic sensibility, it is not surprising that such a God would create a world of great subtlety and beauty at the fundamental level. Given the rule of inference that – all else being equal – a natural non-*ad-hoc* explanation of a phenomenon is always better than no explanation at all, it follows that we should prefer the theistic explanation to the claim that the elegance and beauty of the laws of nature is just a brute fact.¹⁰

26.8 Conclusion

Many scientists feel very uncomfortable, if not hostile, to linking science and religion. As many leading historians have pointed out, however, natural theology and religion were closely linked with scientific practice, and indeed provided much of the inspiration for scientific work, until the late nineteenth century.¹¹

10 For further elaborations of the fine-tuning arguments mentioned in this chapter, with answers to various objections, see my fine-tuning website at www.fine-tuning.org.

11 See, for example, the book by John Brooke and Geoffrey Cantor [32]. For additional work concerning the relation between science and religion from the Middle Ages onward, see the books by Edward Grant [33] and David C. Lindberg [34, 35]. As the evolutionary biologist H. Allen Orr says in his recent review [36] of Richard Dawkins recent book *A Devil's Chaplain: Reflections on Hope, Lies, Science, and Love*:

The popular impression of long warfare between Church and science – in which an ignorant institution fought to keep a fledgling science from escaping the Dark Ages – is nonsense, little more than Victorian propaganda. The truth, which emerged only from the last [twentieth] century of scholarship, is almost entirely unknown among scientists: the medieval Church was

This unease with a science/religion dialogue extends to an unease with publicly discussing anything metaphysical at all in relation to science, including such topics as the anthropic principle and the multiverse hypothesis. On careful analysis of the overall purpose of doing science, however, I think it becomes clear that scientists should be talking about these issues, and doing so in dialogue with other thinkers, such as philosophers and theologians. To see this, note that science could roughly be divided into those aspects which have practical, technological consequences, and those aspects that are at present of merely theoretical interest. What justifies the highly theoretical branches of science, such as current cosmology? One justification is that we cannot know for sure whether these highly abstract studies will eventually lead to technological innovations that contribute to human flourishing. I do not believe, however, that such a far-off hope is sufficient to maintain the broad public support for these theoretical branches of science necessary to retain both funding for publications and student interest. This is especially true given other pressing needs, such as cancer research, for which the payoff is much more immediate.

The other major purpose of science is to help fulfil the human desire to understand the world, which forms a crucial aspect of what could be called ‘human flourishing needs’. These needs consist of meaning, understanding, transcendence, connectedness, belonging, growth and creativity. For many people, these are more important than mere survival needs – such as food and shelter – as demonstrated by the willingness of people throughout history to risk their lives for a cause that gives them purpose. Since these needs must be addressed, our only alternatives are to address them through developing overarching stories of human life and its place in the cosmos that incorporate the best that science has to offer, or by stories lacking such critical input. Bringing our scientific understanding into this larger context, I believe, will serve to sustain and invigorate public interest and support of science, especially in its more theoretical branches.

Addressing these human flourishing needs lies at the core of religion, though often religion has neglected and hampered the need for growth and

a leading patron of science; most theologians studied ‘natural philosophy’; and the medieval curriculum was perhaps the most scientific in Western history.

Further, as pointed out by historians Frances Yates [37] and Robert Merton [38], belief in God is largely responsible for the assumption during the scientific revolution and beyond that the Universe is both harmoniously designed and accessible to human reason, an assumption that lies at the foundation of scientific practice. Science was seen as a way of revealing God’s handiwork in creation. This was especially true in England. Thus, the current dogma forbidding the mutual positive interaction between science and religion does not appear to be intrinsic to science unless one takes the highly presumptuous view that until the late nineteenth century, scientists did not really understand the nature of science.

creativity and given problematic answers to these other needs. Further, religion has typically relied on revelation and common deep human intuitions about the nature of reality as its starting point in understanding the world, whereas science has relied on sense experience and its own methodology in forming hypotheses based on those experiences. Since these needs are common to human beings, they provide a very broad context for science–religion dialogue without requiring knowledge of some particular religious tradition and its sacred texts. Of course, discussions relating to particular religious traditions can still proceed, but these would not comprise the core of the dialogue.

Finally, although discussions of the existence and nature of God are certainly critically relevant to the issue of meaning and purpose in the cosmos, these issues can also be discussed without invoking God. For example, non-theistic understandings of meaning and purpose in the cosmos have been explored by philosophers Quentin Smith [39] and Milton Munitz [40], biologist Ursula Goodenough [41] and (to some extent) physicist Paul Davies [42]. This article should therefore be understood as a contribution to this larger discussion, not merely as an apology for a theistic perspective. I hope this chapter provides some understanding of why a theist might not only be sympathetic to the multiverse hypothesis, but might even see some of the findings of physics and cosmology as supportive of theism.

References

- [1] S. Weinberg. This volume (2007).
- [2] N. Bostrom. This volume (2007).
- [3] A. Vilenkin. This volume (2007).
- [4] J. Polkinghorne. *Belief in God in an Age of Science* (New Haven: Yale University Press, 1998), pp. 1–12.
- [5] M. Tegmark. This volume (2007).
- [6] D. Lewis. *On the Plurality of Worlds* (New York: Basil Blackwell, 1986).
- [7] A. Koyré. *From the Closed World to the Infinite Universe* (Baltimore: Johns Hopkins University Press, 1957), p. 42.
- [8] M. Crowe. *The Extraterrestrial Life Debate, 1750–1900: The Idea of the Plurality of Worlds from Kant to Lowell* (Cambridge: Cambridge University Press, 1986), p. 37.
- [9] L. Susskind. *The Cosmic Landscape, String Theory and the Illusion of Intelligent Design* (New York: Little, Brown and Company, 2005).
- [10] R. Collins. God, design, and fine-tuning. In *God Matters: Readings in the Philosophy of Religion*, eds. R. Martin and C. Bernard (New York: Longman Press, 2002).
- [11] A. W. F. Edwards *Likelihood* (Baltimore: Johns Hopkins University Press, 1973).

- [12] D. H. Mellor. Too many universes. In *God and Design: The Teleological Argument and Modern Science*, ed. N. Mason (London: Routledge, 2003).
- [13] J. M. Keynes. *A Treatise on Probability* (London: Macmillan, 1921), p. 4.
- [14] A. Plantinga. *Warrant and Proper Function* (Oxford: Oxford University Press, 1993), chaps. 8 and 9.
- [15] R. Swinburne. *The Existence of God* (Oxford: Clarendon Press, 1979), pp. 97–102.
- [16] J. Leslie. *Universes* (New York: Routledge, 1989), chap. 8.
- [17] J. Leslie. *Infinite Minds: A Philosophical Cosmology* (Oxford: Clarendon Press, 2001).
- [18] R. Collins. Theism or pantheism? A review essay on John Leslie's 'Infinite Minds'. *Philosophia Christi*, **5** (2003), 563.
- [19] J. Leslie. Pantheism and Platonic creation. A reply to Robin Collins. *Philosophia Christi*, **5** (2003), 575.
- [20] J. Peacock. *Cosmological Physics* (Cambridge: Cambridge University Press, 1999), p. 2.
- [21] L. Susskind. This volume (2007).
- [22] A. Linde. *Particle Physics and Inflationary Cosmology* (Pennsylvania: Harwood Academic Publishers, 1990), p. 33.
- [23] A. Linde. *Inflation and Quantum Cosmology* (New York: Academic Press, 1990), p. 6.
- [24] S. Weinberg. *Dreams of a Final Theory* (New York: Vintage Books, 1992).
- [25] W. Hogarth. *The Analysis of Beauty* (London: J. Reeves, 1753).
- [26] M. Kline. *Mathematical Thought, from Ancient to Modern Times, Vol. 1* (Oxford: Oxford University Press, 1972), p. 153.
- [27] I. Aitchison and A. Hey. *Gauge Theories in Particle Physics, a Practical Introduction*, 2nd edn (Bristol: Adam Hilger, 1989), p. 60.
- [28] A. Guth. *The Inflationary Universe, The Quest for a New Theory of Cosmic Origins* (New York: Helix Books, 1997), p. 124.
- [29] R. Harré and E. Madden. *Causal Powers, Theory of Natural Necessity* (Oxford: Basil Blackwell, 1975).
- [30] M. Tegmark. Parallel universes. In *Science and Ultimate Reality*, eds. J. D. Barrow, P. C. W. Davies and C. L. Harper (Cambridge: Cambridge University Press, 2004), p. 488 [astro-ph/030213].
- [31] C. Misner, K. Thorne and J. Wheeler. *Gravitation* (San Francisco: W. H. Freeman & Co, 1973), pp. 302–303.
- [32] J. Brooke and G. Cantor. *Reconstructing Nature, the Engagement of Science and Religion* (Oxford: Oxford University Press, 1998).
- [33] E. Grant. *The Foundations of Modern Science in the Middle Ages* (Cambridge: Cambridge University Press, 1996).
- [34] D. C. Lindberg. *The Beginnings of Western Science* (Chicago: University of Chicago Press, 1992).
- [35] D. C. Lindberg. *God and Nature: Historical Essays on the Encounter Between Christianity and Science*, eds. D. C. Lindberg and R. L. Numbers (Los Angeles, CA: University of California Press, 1986).
- [36] A. H. Orr. A passion for evolution. *New York Review of Books* **51** (February 26, 2004).
- [37] F. Yates. *Giordano Bruno and the Hermetic Tradition* (Chicago, IL: Chicago University Press, 1964).

- [38] R. Merton. Science, technology, and society in 17th century England. *Osiris*, 4 (1938), 360.
- [39] Q. Smith. *The Felt Meanings of the World, a Metaphysics of Feeling* (West Lafayette, ID: Purdue University Press, 1986).
- [40] M. K. Munitz. *Cosmic Understanding, Philosophy and Science of the Universe* (Princeton: Princeton University Press, 1986).
- [41] U. Goodenough. *The Sacred Depths of Nature* (New York: Oxford University Press, 1998).
- [42] P. Davies. Traveling through time. In *Science and Theology News* (July 1, 2001); www.stnews.org/Commentary-731.htm.

Living in a simulated universe

John D. Barrow

Centre for Mathematical Sciences, Cambridge University

27.1 Introduction

A good point of philosophy is to start with something so simple as not to seem worth stating, and to end with something so paradoxical that no one will believe it.

Bertrand Russell

Of late, there has been much interest in multiverses. What sorts could there be? And how might their existence help us to understand those life-supporting features of our own universe that would otherwise appear to be merely very fortuitous coincidences [1, 2]? At root, these questions are not ultimately matters of opinion or idle speculation. The underlying Theory of Everything, if it exists, may require many properties of our universe to have been selected at random, by symmetry-breaking, from a large collection of possibilities, and the vacuum state may be far from unique.

The favoured inflationary cosmological model – that has been so impressively supported by observations of the COBE and WMAP satellites – contains many apparent ‘coincidences’ that allow our universe to support complexity and life. If we were to consider a ‘multiverse’ of all possible universes, then our observed universe appears special in many ways. Modern quantum physics even provides ways in which the possible universes that make up the multiverse of all possibilities can actually exist.

Once you take seriously that all possible universes can (or do) exist, then a slippery slope opens up before you. It has long been recognized that technical civilizations, only a little more advanced than ourselves, will have the capability to simulate universes in which self-conscious entities can emerge and communicate with one another [3]. They would have computer power that exceeded ours by a vast factor. Instead of merely simulating their weather or the formation of galaxies, like we do, they would be able to go further and watch the appearance of stars and planetary systems. Then, having coupled

the rules of biochemistry into their astronomical simulations, they would be able to watch the evolution of life and consciousness – all speeded up to occur on whatever timescale was convenient for them. Just as we watch the life cycles of fruit flies, they would be able to follow the evolution of life, watch civilizations grow and communicate with each other and argue about whether there existed a Great Programmer in the Sky who created their universe and who could intervene at will in defiance of the laws of nature they habitually observed.

Once this capability to simulate universes is achieved, fake universes will proliferate and will soon greatly outnumber the real ones. Thus Nick Bostrom [4, 5] and Brian Weatherson [6] have argued that a thinking being here and now is more likely to be in a simulated reality than a real one. Motivated by this alarming conclusion, there have even been suggestions as how best to conduct ourselves if we have a high probability of being simulated beings in a simulated reality. Robin Hanson [7] suggests that you should act so as to increase the chances of continuing to exist in the simulation or of being resimulated in the future:

If you might be living in a simulation, then all else equal you should care less about others, live more for today, make your world look more likely to become rich, expect to and try more to participate in pivotal events, be more entertaining and praiseworthy, and keep the famous people around you happier and more interested in you.

In response, Paul Davies [8, 9] has argued that this high probability of living in a simulated reality is a *reductio ad absurdum* for the whole idea that multiverses of all possibilities exist. It would undermine our hopes of acquiring any sure knowledge about our universe.

The multiverse scenario was originally suggested by some cosmologists as a way to avoid the conclusion that our universe was specially designed for life by a Grand Designer. Others saw it as a way to avoid having to say anything more about the problem of fine-tuning at all. However, we see that once conscious observers are allowed to intervene in our universe, rather than being merely lumped into the category of ‘observers’ who do nothing, we end up with a scenario in which the gods reappear in unlimited numbers in the guise of the simulators who have power of life and death over the simulated realities that they bring into being. The simulators determine the laws, and can change the laws, that govern their worlds. They can engineer anthropic fine-tunings [10]. They can pull the plug on the simulation at any moment; intervene or distance themselves from their simulation; watch as the simulated creatures argue about whether there is a god who controls

or intervenes; work miracles or impose their ethical principles upon the simulated reality. All the time they can avoid having even a twinge of conscience about hurting anyone because their toy reality is not real. They can even watch their simulated realities grow to a level of sophistication that allows them to simulate higher-order realities of their own.

27.2 How would we tell if we lived in a simulation?

Faced with these perplexities, do we have any chance of winnowing fake realities from true? What might we expect to see if we made scientific observations from within a simulated reality?

Firstly, the simulators will have been tempted to avoid the complexity of using a consistent set of laws of nature in their worlds when they can simply patch in ‘realistic’ effects. When the Disney company makes a film that features the reflection of light from the surface of a lake, it does not use the laws of quantum electrodynamics and optics to compute the light scattering. That would require a stupendous amount of computing power and detail. Instead, the simulation of the light scattering is replaced by plausible rules of thumb that are much briefer than the real thing but give a realistic looking result – as long as no one looks too closely. There would be an economic and practical imperative for simulated realities to stay that way if they were purely for entertainment. But such limitations to the complexity of the simulations programming would presumably cause occasional tell-tale problems; perhaps they would even be visible from within.

Even if the simulators were scrupulous about simulating the laws of nature, there would be limits to what they could do. Assuming the simulators, or at least the early generations of them, have a very advanced knowledge of the laws of nature, it is likely they would still have incomplete knowledge of them (some philosophers of science would argue this must always be the case). They may know a lot about the physics and programming needed to simulate a universe, but there will be gaps or, worse still, errors in their knowledge of the laws of nature. These would, of course, be subtle and far from obvious; otherwise our ‘advanced’ civilization would not be advanced. These lacunae would not prevent simulations being created and running smoothly for long periods of time. But gradually the little flaws would begin to build up.

Eventually, their effects would snowball, and these realities would cease to compute. The only escape is if their creators intervene to patch up the problems one by one as they arise. This is a solution that will be very familiar to the owner of any home computer who receives regular updates

in order to protect it against new forms of invasion or repairs gaps that its original creators had not foreseen. The creators of a simulation could offer this type of temporary protection, updating the working laws of nature to include extra things they had learnt since the simulation was initiated.

In this kind of situation, logical contradictions will inevitably arise and the laws in the simulations will appear to break down now and again. The inhabitants of the simulation – especially the simulated scientists – will occasionally be puzzled by the experimental results they obtain. The simulated astronomers might, for instance, make observations that show that their so-called constants of nature are very slowly changing.¹

It is likely that there could even be sudden glitches in the laws that govern these simulated realities. This is because the simulators would most likely use a technique that has been found to be effective in all other simulations of complex systems: the use of error-correcting codes to put things back on track.

Take our genetic code, for example. If it were left to its own devices, we would not last very long. Errors would accumulate and death and mutation would quickly follow. We are protected from this by the existence of a mechanism for error-correction that identifies and corrects mistakes in genetic coding. Many of our complex computer systems possess the same type of internal spell-checker to guard against error accumulation.

If the simulators used error-correcting computer codes to guard against the fallibility of their simulations as a whole (as well as simulating them on a smaller scale in our genetic code), then every so often a correction would take place to the state or the laws governing the simulation. Mysterious sudden changes would occur that would appear to contravene the very laws of nature that the simulated scientists were in the habit of observing and predicting.

We might also expect that simulated realities would possess a similar level of maximum computational complexity across the board. The simulated creatures should have a similar complexity to the most complex simulated non-living structures – something that Stephen Wolfram [14] (for

¹ There is tantalizing evidence that there might be small changes in some of our constants of nature, notably the fine structure constant, by a few parts in a million over the 14 billion year age of our universe. The fundamental perspective provided by string theory leads us to expect that space has more dimensions than the three large ones that we observe directly. This means that the true constants of nature exist in the total number of dimensions and that the 3-dimensional ‘constants’ that we have defined are merely ‘shadows’ that do not need to be constant. In fact, if the extra dimensions of space were to change in time in any way, then our 3-dimensional constants would be seen to change at the same rate. For the observational evidence for such changes, see refs. [11]–[13].

quite different reasons, nothing to do with simulated realities) has coined the Principle of Computational Equivalence.

One of the most common worries about distinguishing a simulated reality from a true one from the inside is the suggestion that the simulators would be able to take into account some difference one might think of ahead of time and pre-adjust the simulation to avoid the mismatch. This new simulated reality might then develop its own disparities with true reality, but they would be plugged by another act of predestination. The question is whether this is possible in the limit where the number of these adjustments becomes arbitrarily large. The problem is similar to that first considered by Karl Popper [15] to identify the self-referential limits of computers. The same argument was used in a different context in many publications by the late Donald MacKay [16] as an argument against the possibility of predestination, if this is knowable by those whose futures are being predicted. It is only possible to make a correct prediction of someone's future actions if it is not made known to them [17]. Once it is made known, it is always possible for them to falsify it. Thus, it is not possible for there to be an unconditionally binding prediction of someone's future actions. Clearly the same argument applies to predicting elections:² there cannot be a public prediction of the outcome of an election that unconditionally takes into account the effect of the prediction itself on the electorate. This type of uncertainty is irreducible in principle. If the prediction is not made public, it could be 100% correct.

So we suggest that, if we live in a simulated reality, we should expect occasional sudden glitches, small drifts in the supposed constants and laws of nature over time [21], and a dawning realization that the flaws of nature are as important as the laws of nature for our understanding of true reality.

References

- [1] M. Tegmark. Parallel universes. *Sci. Am.* (May 2003), pp. 41–51.
- [2] M. J. Rees. *Our Cosmic Habitat* (Princeton, NJ: Princeton University Press, 2001).
- [3] J. D. Barrow. *Pi in the Sky: Counting, Thinking and Being* (Oxford: Oxford University Press, 1992), chap. 6.
- [4] N. Bostrom. Are you living in a computer simulation? *Phil. Quart.* **53** (2003), 243.
- [5] N. Bostrom. The simulation argument: Reply to Weatherson. *Phil. Quart.* **55**, (2005), 90.
- [6] B. Weatherson. Are you a sim? *Phil. Quart.* **53** (2003), 425.

² Although there is a famous false argument by Herbert Simon claiming the opposite [18]; it is also reprinted in ref. [19]. The fallacy arose because of the illicit use of the fixed point theorem of Brouwer in a situation where the variables are discrete rather than continuous. See ref. [20] for a detailed explanation.

- [7] R. Hanson. How to live in a simulation. *J. Evolution and Technology* **7** (2001) [<http://www.transhumanist.com>].
- [8] P. C. W. Davies. A brief history of the multiverse. *New York Times* (April 12, 2003).
- [9] P. C. W. Davies. This volume (2007).
- [10] E. R. Harrison. The natural selection of universes containing intelligent life. *Quart. J. Roy. Astron. Soc.* **36** (1995), 193.
- [11] J. D. Barrow and J. K. Webb. Inconstant constants. *Sci. Am.* (June 2005), pp. 56–63.
- [12] J. K. Webb, M. T. Murphy, V. V. Flambaum *et al.* Further evidence for cosmological evolution of the fine structure constant. *Phys. Rev. Lett.* **87** (2001), 091301.
- [13] E. Reinhold, R. Buning, U. Hollenstein, A. Ivanchik, P. Petitjean and W. Ulbachs. Indication of a cosmological variation of the proton-electron mass ratio based on laboratory measurement and reanalysis of H_2 spectra. *Phys. Rev. Lett.* **96** (2006), 151101.
- [14] S. Wolfram. *A New Kind of Science* (Chicago, IL: Wolfram Inc., 2002).
- [15] K. Popper. Indeterminism in quantum physics and in classical physics. *Brit. J. Phil. Sci.* **1** (1950), 117, 173.
- [16] D. MacKay. *The Clockwork Image* (London: IVP, 1974), p. 110.
- [17] J. D. Barrow. *Impossibility* (Oxford: Oxford University Press, 1988), chap. 8.
- [18] H. Simon. Bandwagon and underdog effects in election predictions. *Public Opinion Quart.* **18** (Fall issue, 1954), 245.
- [19] S. Brams. *Paradoxes in Politics* (NY: Free Press, 1976), pp. 70–7.
- [20] K. Aubert. Spurious mathematical modelling. *The Mathematical Intelligencer*, **6** (1984), 59.
- [21] J. D. Barrow. *The Constants of Nature: From Alpha to Omega* (London: Jonathan Cape, 2002).

Universes galore: where will it all end?

Paul Davies

Australian Centre for Astrobiology, Macquarie University

28.1 Some sort of philosophy is inescapable

Most scientists concede that there are features of the observed Universe which appear contrived or ingeniously and felicitously arranged in their relationship to the existence of biological organisms in general and intelligent observers in particular. Often these features involve so-called fine-tuning in certain parameters, such as particle masses or coupling constants, or in the cosmic initial conditions, without which life (at least life as we know it) would be either impossible or very improbable. I term this state of affairs bio-friendliness or biophilicity. Examples of such fine-tuning have been thoroughly reviewed elsewhere [1] and in this volume, so I will not list them here.

It is normally remarked that cosmic bio-friendliness has two possible explanations (discounting sheer luck). One is that the Universe has been designed by a pre-existing creator with life in mind. The other, which is often motivated explicitly or implicitly by a reaction to supernatural explanations, is the multiverse. According to the latter explanation, what we call ‘the Universe’ is but a small component in a vastly larger assemblage of ‘universes’, or cosmic regions, among which all manner of different physical laws and conditions are somewhere instantiated. Only in those ‘Goldilocks’ regions where, by accident, the numbers come out just right will observers like ourselves arise and marvel at the ingenious arrangement of things. Thus the reason why we observe a universe so suspiciously contrived for life is because we obviously cannot observe one that is inimical to life. This is the so-called anthropic, or biophilic selection, principle [2].

Before reviewing the pros and cons of the multiverse explanation, I should like to make a general point. All cosmological models are constructed by augmenting the results of observations by some sort of philosophical principle. Two examples from modern scientific cosmology are the principle

of mediocrity, sometimes known as the Copernican principle, and the biophilic selection principle. The principle of mediocrity states that the portion of the Universe we observe is not special or privileged, but is representative of the whole. Ever since Copernicus demonstrated that Earth does not lie at the centre of the Universe, the principle of mediocrity has been the default assumption; indeed, it is normally referred to as simply the ‘cosmological principle’. It underpins the standard Friedmann–Robertson–Walker cosmological models.

In recent years, however, an increasing number of cosmologists have stressed the inherent limitations of the principle of mediocrity. Scientific observations necessarily involve observer selection effects, especially in astronomy. One unavoidable selection effect is that our location in the Universe must be consistent with the existence of observers. In the case of humans at least, observers imply life. (There is no reason why non-living observers could not exist, and indeed we may conjecture that advanced technological communities may create them. However, it is normally assumed that the emergence of life and intelligence is a precursor to the creation of non-living sentient beings, although there is no logical impediment to abiological sentience arising *de novo*.) Stated this way – that the Universe we observe must be consistent with the existence of observers – the biophilic principle seems to be merely a tautology. However, it carries non-trivial meaning when we drop the tacit assumption that the Universe, and the laws of nature, necessarily assume the form that we observe. If the Universe and its laws could have been otherwise, then one explanation for why they are as they are might be that we (the observers) have selected it from a large ensemble of alternatives.

This biophilic selection principle becomes more concrete when combined with the assumption that what we have hitherto regarded as absolute and universal laws of physics are, in fact, more like local by-laws: they are valid in our particular cosmic patch, but they might be different in other regions of space and/or time [3]. This general concept of ‘variable laws’ has been given explicit expression through certain recent theories of cosmology and particle physics, especially by combining string/M-theory with inflationary cosmology. There is little observational evidence for a domain structure of the Universe within the scale of a Hubble volume, but on a much larger scale there could exist domains in which the coupling constants and particle masses in the Standard Model may be inconsistent with life. It would then be no surprise that we find ourselves located in a (possibly atypical) life-encouraging domain, as we could obviously not be located where life was impossible.

Once it is conceded that the Universe could have been otherwise – that the laws of physics and the cosmic initial conditions did not have to assume the form we observe – then a second philosophical issue arises. The multiverse will contain a set of ‘universes’ that serve as instantiations for certain laws and initial conditions. What, then, determines the selection of universes on offer? Or to express it more graphically, using Stephen Hawking’s words [4]: ‘What is it that breathes fire into the equations and makes a universe for them to govern?’

Only two ‘natural’ states of affairs commend themselves in this regard. The first is that nothing exists; the second is that everything exists. The former we may rule out on observational grounds. So might it be the case that everything that can exist, does exist? That is indeed the hypothesis proposed by some cosmologists, most notably Max Tegmark [5]. At first sight this hypothesis appears extravagant. The problem, however, for those who would reject it is that, if *less* than everything exists, then there must be some rule that divides those things that actually exist from those that are merely possible but are in fact non-existent. One is bound to ask: What would this rule be? Where would it come from? And why *that* rule rather than some other?

28.2 An old-fashioned Cosmic Designer is a poor explanation

Since most of the contributions to this volume are written from a scientific perspective, I shall not dwell at length on why one might feel uncomfortable with the crude idea of a Cosmic Designer who contemplates a ‘shopping list’ of possible universes, figures out one that will contain life and observers, and then sets to work creating it, discarding the alternatives. The central objection to the hypothesis is its *ad hoc* nature. Unless one already has some other reason to believe in the existence of the Designer, then merely declaring ‘God did it!’ tells us nothing at all.

It has been argued (see, for example, ref. [6]) that an infinite God is a simpler explanation for existence than just accepting the universe as a brute fact, and therefore to be preferred on the grounds of Ockham’s razor. Dawkins [7] has countered that God must be at least as complex as the system that God creates. But considerable care is needed in using terms like ‘simple’ and ‘complex’. A branch of mathematics called algorithmic complexity theory [8] can be used to provide rigorous definitions of simplicity and complexity. One surprising feature of these definitions is that the whole can

sometimes be simpler than its component parts. Thus, God-plus-Universe can be simpler than either God or the Universe in isolation. I shall return to this topic in Section 28.3.5.

A further difficulty with divine selection concerns the notion of free choice. Christian theologians traditionally assert that God is a *necessary* being (see, for example, ref. [9]), i.e. it is logically impossible for God not to exist. If so, we are invited to believe that a necessary being did not necessarily create the Universe as it is (otherwise there is no element of choice and nature is reduced to a subset of the divine being rather than a creation of this being). But can a necessary being act in a manner that is not necessary? On the other hand, if God is regarded as not necessary but contingent, then on what, precisely, is God's existence and nature contingent? If we do not ask, we gain nothing by invoking such a contingent God, whose existence would then have to be accepted as a brute fact. One might as well simply accept a contingent universe as a brute fact, and be done with it. If we do ask, then we accept that reality is larger than God and that an account of the Universe must involve explanatory elements beyond God's being. But if we accept the existence of such explanatory elements, why is there any need to invoke divine elements also?

There is a long tradition of attempts to reconcile a necessary God with a contingent single universe (see, for example, ref. [10]). But one is bound to ask, even if such reconciliation were possible, why God freely chose to make this universe rather than some other. If the choice is purely whimsical, then the Universe is absurd and reasonless once more. On the other hand, if the choice proceeds from God's nature (for example, a good God might make a universe inhabited by sentient beings capable of joy), then one must surely ask: *Why* was God's nature such as to lead to *this* choice of universe rather than some other? This further worry would be addressed, in turn, only by proving – not only that God exists necessarily – but that God's entire nature is also necessary. Such a conclusion would entail proving that, for example, an evil creator capable of making a world full of suffering is not merely undesirable but *logically impossible*.

28.3 Shortcomings of anthropic/multiverse explanations

If theological explanations for cosmic biophilicity are problematic, then multiverse explanations are not without their difficulties too. In what follows, I shall review some of the challenges that have been made to multiverse/anthropic reasoning.

28.3.1 *It's not science because it's not testable*

It is sometimes objected that, because our observations are limited to a single universe (e.g. a Hubble volume), then the existence of 'other universes' cannot be observed, and so their existence cannot be considered a proper scientific hypothesis. Even taking into account the fact that future observers will see a larger particle horizon, and so have access to a bigger volume of space, most regions of the multiverse (at least in the eternal inflation model) can never be observed, even in principle. While this may indeed preclude direct confirmation of the multiverse hypothesis, it does not rule out the possibility that it may be tested indirectly. Almost all scientists and philosophers accept the general principle that the prediction of unobservable entities is an acceptable scientific hypothesis if those entities stem from a theory that has other testable consequences. At this stage, string/M-theory does not have any clear-cut experimental predictions, but one may imagine that a future elaboration of the theory would produce testable consequences. These theories are not idle speculations, but emerge from carefully considered theoretical models with some empirical justification.

A test of the multiverse hypothesis may be attained by combining it with biophilic selection. This leads to statistical predictions about the observed values of physical parameters [3]. If we inhabit a typical biophilic region of the multiverse, we would expect any biologically relevant adjustable parameters to assume typical values. If one considers a vast parameter space of possible universes, there will be one or more biophilic patches – or subsets – of the space, and a typical biophilic universe would not lie *close to the centre* of such a patch (i.e. it would not be *optimally biophilic*). In other words, there is no *a priori* reason why the laws of physics should be more bio-friendly than is strictly necessary for observers to arise. If, therefore, we discovered that some parameter (such as the amount of dark energy) assumed a value in a tiny subset located deep inside the biophilic parameter range, this would be evidence against it being a random variable that had been anthropically selected.

There is a hidden assumption in the foregoing reasoning, which is that life originates only once in each universe. If life happens many times, then optimally biophilic universes may contain many more observers than *minimally* biophilic universes, and this weighting factor must be taken into account when considering a randomly chosen observer. We must now distinguish between biophilicity in relation to *laws* and biophilicity in relation to *contingency*. Regarding the latter, it is possible that life is indeed 'a damned close-run thing' (to paraphrase Lord Wellington) – a statistical fluke, unique in the observable Universe, arising from a highly improbable molecular accident.

If, however, we discover a second genesis of life – an independent origin on a nearby planet – then this would imply that the Universe is teeming with life and is at least *near*-optimally biophilic in relation to contingency.

But even in the absence of any data concerning multiple geneses, we may still consider biophilicity in relation to the laws of the Universe. At first glance, there is little reason to suppose that the Universe is minimally biophilic in this respect. Take the much-cited example of carbon abundance. The existence of carbon as a long-lived element depends on the ratio of electromagnetic to strong nuclear forces, which determines the stability of the nucleus. But nuclei much heavier than carbon are stable, so the life-giving element lies comfortably within the stability range. The electromagnetic force could be substantially stronger, without threatening the stability of carbon. Now, it is true that, if it were stronger, then the specific nuclear resonance responsible for abundant carbon would be inoperable, but it is not clear how serious this would be. Life could arise in a universe where carbon was merely a trace element, or abundant carbon could occur because of different nuclear resonances. Of course, if it could be shown that other, heavier, elements are essential for life, this objection would disappear. (The prediction that much heavier elements are essential for life could be an interesting prediction of the multiverse theory.)

A simpler example is the amount of dark energy in the Universe. Once again, the observed value is comfortably in the middle of the biologically acceptable parameter range. Theory predicts that the density of dark energy (Λ) should be vastly greater than the observed value, so we might expect in the multiverse explanation that the observed value would be near the top end of the biologically permissible parameter range. But Λ could be an order of magnitude bigger without threatening the existence of galaxies and stars, and hence life [3]. On the face of it, therefore, the observed Universe is not minimally biophilic, and many scientists seem to think it is actually optimally biophilic.

Another consideration concerns the very existence of physical laws. In those versions of the multiverse in which even the appearance of law is attributed to anthropic selection, there is clearly a problem about minimal biophilicity. The multiverse explanation would lead us to expect that we live in a universe that has the minimal degree of order consistent with the existence of observers. Departures from order, or lawfulness, that are not biologically threatening should therefore be permitted. To take a simple example, consider the law of conservation of electric charge. The charge on the electron could happily fluctuate by, say, one part in 10^6 without disrupting biochemistry. In fact, measurement of the anomalous magnetic

moment of the electron fixes the electric charge to eleven significant figures – a stability far in excess of that needed to ensure the viability of living organisms. So either the electric charge is fixed by a law of nature, in which case the multiverse cannot be invoked to explain this particular aspect of cosmic order, or there is some deep linkage between the charge on the electron and some aspect of physics upon which the existence of life depends far more sensitively. But it is hard to see what this might be.

28.3.2 Measures of fine-tuning are meaningless

Intuitively we may feel that some physical parameters are remarkably fine-tuned for life, but can this feeling ever be made mathematically precise? The fact that a variation in the strength of the strong nuclear force by only a few per cent may disrupt the biological prospects for the Universe appears to offer a surprisingly narrow window of biophilic values, but what determines the measure on the space of parameters? If the strength of the nuclear force could, in principle, vary over an infinite range, then any finite window, however large, would be infinitesimally improbable if a uniform probability distribution is adopted. Even the simple expedient of switching from a uniform to a logarithmic distribution can have a dramatic change on the degree of improbability of the observed values, and hence the fineness of the fine-tuning. There will always be an element of judgement involved in assessing the significance, or degree of surprise, that attaches to any given example.

28.3.3 Humans are more than mere observers

Most often discussed in relation to anthropic selection is the matter of fine-tuning of certain physical parameters, such as the relative strengths of the fundamental forces of nature. Had these parameters taken on values outside a relatively narrow range, then it is likely that the Universe would go unobserved. Whilst trivially true, this explanation is unacceptably narrow, because it treats humans as mere observers. That is, it is merely necessary for there to exist observers *of some sort* for the argument to work (the term ‘anthropic’ is an acknowledged misnomer in this respect). Indeed, the application of anthropic reasoning usually ignores even the conditions necessary for intelligent observers to evolve and restricts attention simply to the existence of life.

Humans, however, are more than mere observers. They also have the ability to *understand* the Universe through logical reasoning and the scientific

method [11]. This remarkable fact, often taken for granted by scientists, cannot be explained by anthropic/multiverse reasoning. It is perfectly possible for there to exist a universe that permits the existence of observers who nevertheless do not, or cannot, make much sense of nature. Thus cats and dogs surely qualify as observers, but are not, like humans, privy to the deep mathematical rules on which the Universe runs. Moreover, in a general multiverse scenario, the vast majority of universes that permit the existence of observers with the same intellectual prowess as humans will not be comprehensible to those observers. For example, there are many ways that the laws of physics we observe could be more complex without threatening the existence of biology: non-computability of the laws, forces varying with time in a complicated way that leaves chemistry largely unaffected, legions of additional weak forces that do not substantially affect the formation of galaxies, stars and planets, millions of species of neutrinos, etc. In fact, the physics of the Universe is *extremely special*, inasmuch as it is both simple and comprehensible to the human mind.

28.3.4 *The blunderbuss objection*

It is trivially true that, in an infinite universe, anything that can happen will happen. But this catch-all explanation of a particular feature of the Universe is really no explanation at all. We should like to understand the bio-friendliness of *this* universe. To postulate that all possible universes exist does not advance our understanding at all. A good scientific theory is analogous to a well targeted bullet that selects and explains the object of interest. The multiverse is like a blunder buss – hitting everything in sight.

To put this point into context, imagine that the Universe we observe is divided into Planck-sized three-dimensional cells. Each cell may be assigned a finite set of numbers that determines its state; for example, the amplitudes of all fields at that point. Now imagine that the digits of π are expressed in binary form and used to label the state of each cell in sequence, using as many digits as necessary to specify the field amplitudes to any desired precision. When all cells in the observable Universe have been labelled, a state of the entire Universe is determined. Now imagine that the process is repeated with the further digits of π . Another state is defined. This process may be continued for a stupendous number of steps (Planck times), giving us a ‘cosmic history’. Most of the cosmic history will be random noise, lacking even the semblance of causal order. But, by the very definition of randomness, we are assured that, sooner or later, the observed cosmic history will be generated [12]. So too will *all other* cosmic histories: the digits of π

contain all possible worlds. Should we be satisfied, therefore, that we have explained the Universe, together with all its remarkable features, such as biophilicity, by saying merely that it is a manifestation of π ? Or perhaps of e , or of almost any real number we like to pick? Clearly not. Saying that our world is buried in the limitless noise of the digits of π does not make π a magic generator of reality. It merely highlights the vacuousness of seeking to appeal to everything in order to explain something in particular.

28.3.5 The multiverse is really an old-fashioned God in disguise

In this section, I shall argue that, in a certain mathematical sense, the most general multiverse models (e.g. Tegmark's Level 4 version) are ontologically equivalent to naïve deism, by which I mean the existence of a Cosmic Designer/Selector who judiciously picks a single real universe from an infinite shopping list of possible but unreal universes. Indeed, I suspect the general multiverse explanation is simply naïve deism dressed up in scientific language. Both appeal to an infinite unknown, invisible and unknowable system. Both require an infinite amount of information to be discarded just to explain the (finite) universe we observe. It would be instructive to quantify and compare the degree of credulity we might attach to various competing multiverse and theological models using algorithmic complexity theory. It seems likely that some versions of both the multiverse and naïve deism would be equivalently complex and, in most cases, infinitely complex. They may employ different terminology but, in essence, both explanations are the same. If I am right, then the multiverse is scarcely an improvement on naïve deism as an explanation for the physical universe. It is basically just a religious conviction rather than a scientific argument.

I will make an even stronger claim. I believe that naïve deism and the general multiverse concept will turn out to be of equivalent complexity because *they are contained within each other*. Consider the most general multiverse theories (Tegmark's Level 4), where even laws are abandoned and anything at all can happen. At least some of these universes will feature miraculous events – water turning into wine, etc. They will also contain thoroughly convincing religious experiences, such as direct revelation of a transcendent being. It follows that a general multiverse set must contain a subset that conforms to traditional religious notions of God and design. It could be countered, however, that this subset is embedded in a much bigger set in which no coherent theological plan is discernible, so that a random observer would be unlikely to encounter a world in which a God was seen to

be at work. But this is to ignore the possibility of simulated realities (see Section 28.3.6).

28.3.6 *Real versus fake universes*

The starting point of all anthropic – multiverse arguments is the existence of *observers*. This raises the question of what constitutes an observer. I shall assume that ‘observership’ is a product of physical processes, for example electrochemical activity in the brain. It then follows that observers may be created artificially by sufficiently advanced technology. Possibly this merely requires bigger and better computing systems, as argued by proponents of strong AI; possibly it requires a new form of technology, as argued by Roger Penrose [13]. For my purposes, it does not matter. In a multiverse, there will be a subset of universes in which advanced technology like ours emerges, and a sizeable sub-subset will contain at least one technological civilization that reaches the point of simulating consciousness. It is but a small step from simulating consciousness to simulating a community of conscious beings and an entire virtual world for them to inhabit.

This notion has been popularized in *The Matrix* series of science fiction movies. For any given ‘real’ world, there would be a vast, indeed infinite, number of possible virtual worlds. A randomly selected observer would then be overwhelmingly more likely to experience a virtual simulation than the real thing. Thus there is little reason to suppose that *this* world (the one you and I are observing now) is other than a simulated one [14, 15]. But the denizens of a simulated virtual world stand in the same ontological relationship to the intelligent system that designed and created their world as human beings stand in relation to the traditional Designer/Creator Deity (a fact not lost on science fiction writers from Olaf Stapledon onwards), but with God now in the guise – not of a Grand Architect – but of a Grand Software Engineer. The creator of the virtual worlds is a transcendent designer with the power to create or destroy simulated universes at will, alter the circumstances within them, devise laws, perform miracles, etc. Taken to its logical extreme, the multiverse explanation is a convincing argument for the existence of (a rather old-fashioned form of) God! This is certainly ironical, since it was partly to do away with such a God that the multiverse was originally invoked.

Worse still, there is no end to the hierarchy of levels in which worlds and designers can be embedded. If the Church–Turing thesis is accepted, then simulated systems are every bit as good as the original real universe at simulating their own conscious sub-systems, sub-sub-systems, and so on

ad infinitum: gods and worlds, creators and creatures, in an infinite regress, embedded within each other. We confront something more bewildering than an infinite tower of virtual turtles: a turtle fractal of virtual observers, gods and universes in limitlessly complex inter-relationships. If *this* is the ultimate reality, there would seem to be little point in pursuing scientific inquiry at all into such matters. Indeed, to take such a view is as pointless as solipsism. My point is that to follow the multiverse theory to its logical extreme means effectively abandoning the notion of a rationally ordered real world altogether, in favour of an infinitely complex charade, where the very notion of ‘explanation’ is meaningless.

This is the ‘slippery slope’ referred to by Rees [16]. At one end of the slope is the perfectly unobjectionable idea that there may be regions beyond a Hubble distance that possess, say, a lower average matter density or slightly less dark energy. At the bottom of the slope is the ‘fantasy-verse’ of arbitrary virtual realities, whimsically generated by a pseudo-Deity designer.

28.3.7 Multiverses merely shift the problem up one level

Multiverse proponents are often vague about how the parameter values are chosen across the defined ensemble. If there is a ‘law of laws’ describing how parameter values are assigned as one slips from one universe to the next, then we have only shifted the problem of cosmic biophilicity up one level. Why? First, because we need to explain where the law of laws comes from. But there is a second problem. Each law of laws specifies a different version of the multiverse, and not all multiverses are bound to contain at least one biophilic universe. In fact, on the face of it, most multiverses would *not* contain even one component universe in which all the parameter values were suitable for life. To see this, note that each parameter will have a small range of values – envisage it as a highlighted segment on a line – consistent with biology. Only in universes where all the relevant highlighted segments intersect in a single patch (i.e. all biophilic values are instantiated together) will biology be possible. If the several parameters vary *independently* between universes, each according to some rule, then for most sets of rules the highlighted segments will not concur. So we must not only explain why there is any law of laws; we must also explain why the actual law of laws (i.e. the actual multiverse) happens to be one that intersects the requisite patch of parameter space that permits life.

Often it is asserted that there is no law of laws, only randomness. Thus in Smolin’s version of the multiverse, gravitational collapse events ‘reprocess’ the existing laws with small random variations [17]. In this case, given

an infinite multiverse, randomness would ensure that at least one biophilic universe exists with a finite (albeit minute) probability. (That is, there will always be a patch of parameter space somewhere with all highlighted segments intersecting.) Plausible though this is, the assumption of randomness is not without its problems. Without a proper measure over the parameter space, probabilities cannot be properly defined. There is a danger of predicting meaningless or paradoxical results. There is also a danger in some multiverse models that the biophilic target universes may form only a set of measure zero in the parameter space, and thus be only infinitesimally probable. Furthermore, in some models, various randomness measures may be inconsistent with the underlying physics. For example, in the model of a single spatially infinite Universe in which different supra-Hubble regions possess different total matter densities, it is inconsistent to apply the rule that any value of the density may be chosen randomly in the interval $[0, \rho]$, where ρ is some arbitrarily large density (e.g. the Planck density). The reason is that for all densities above a critical value (very low compared with the Planck density), the Universe is spatially finite, and so inconsistent with the assumption of an infinite number of finite spatial regions [18].

The need to rule out these ‘no-go’ zones of the parameter space imposes restrictions on the properties of the multiverse that are tantamount to the application of an additional overarching biophilic principle. There would seem to be little point in invoking an infinity of universes only then to impose biophilic restrictions at the multiverse level. It would be simpler to postulate a single universe with a biophilic principle.

28.4 The third way

Considerations of anthropic fine-tuning seek to explain the appearance of an otherwise puzzling link between the universe on one hand and life on the other. Why should there be a connection? What does the Universe know about life? What do the laws of physics care about consciousness?

The most obvious way to establish a link between life and cosmos is to postulate a ‘life principle’ (or, extending this to encompass observers, a ‘mind principle’). Indeed, many scientists have suggested just such a thing. It is often claimed by astrobiologists that life is ‘written into the laws of physics’ or ‘built into the nature of the Universe’ [19]. Thus Sydney Fox, in his theory of biogenesis, claimed that the laws of physics and chemistry were rigged in favour of those reactions that lead to life [20]. Others, such as Christian de Duve [21] and Stuart Kauffman [22], have hinted that somehow chemistry favours life and can fast-track matter and energy to the living state.

John Wheeler, in his ‘participatory universe’ principle, has even claimed something along those lines for mind [23].

Is there any evidence for such a principle? The laws of physics, as we now understand them, do not offer much promise in this regard. The reason is not hard to find. Life is incredibly complex but the laws of physics are, in the algorithmic sense, simple. So life cannot be contained in the laws of physics. Contrast this with another state of matter: crystals. The structures of crystals are determined by the symmetries of the electromagnetic force, and so they *are* built into the laws of physics. Basic geometry underlies them. Given the laws of physics, the structure of, say, common salt crystals may be deduced from purely geometrical considerations. Crystals are simple and have low information content, concordant with the low information content of the laws of physics. But one could not predict the structure of, say, a bacterium, nor even its genome sequence, from the laws of physics, because the genome has very high information content. It was for that sound mathematical reason that Jacques Monod declared ‘we are alone’ and ‘the Universe is not pregnant with life’. In his opinion, life is just a stupendously improbable accident [24].

The root cause of the difficulty goes back at least to the time of Newton and the deep dualism that pervades all of science: the dualism between eternal universal laws and time-dependent contingent states. Because laws are general, simple, low in information content and unchanging with time, most specific states of matter cannot be built into them. States of matter are generally local, special, complex, high in information content and time-dependent. So the very structure of traditional scientific explanation precludes our finding a direct link between the underlying laws of the Universe (as we at present understand them) and the emergence of an exceedingly specific and peculiar state of matter such as ‘life’ – still less an even more specific and peculiar state such as ‘mind’. Therefore, if we wish to postulate such a link, then the traditional dualism of laws and states must go.

Aristotle did not make a sharp distinction between laws and states. By introducing different categories of causation, and specifically by including final causes, he could speculate on how the Universe might develop in a directed manner toward certain special states. For Aristotle, life was indeed built into the nature of the Universe through final causation. Such goal-directed or purposeful influences in nature are termed *teleological* by philosophers.

The assumption of a link between laws and product states such as life inevitably amounts to slipping an element of teleology into physics. This is very unfashionable, but I believe it is unavoidable if we are to take life

and mind seriously as *fundamental* rather than *incidental* features of the Universe. And the bio-friendliness of the Universe suggests that they *are* fundamental. We need not be as crude as Aristotle, by nailing down the final state in advance and constraining the Universe to generate it; de Duve, for example, has suggested in the context of biological evolution that the general trend (e.g. from simple to complex, from mindless to mental) is law-like, although the specific details are contingent [21]. In my essay ‘The physics of downward causation’ [25], I have suggested that such a felicitous mix of law and chance might be generalized to cosmology, producing directional evolution from simple through complex states, to life and mind.

Obviously these are just words, whereas what is required are concrete mathematical models. To investigate the basic ideas, I have developed some cellular automaton models with the help of Neil Rabinowitz. Recall that, in a conventional cellular automaton system, one starts with a 1-dimensional array of cells, or pixels, each of which can be in one of two states: filled or unfilled (‘on’ or ‘off’). An update rule is specified that determines whether a given pixel remains on or off, is switched from on to off or vice versa. This rule is based on the state of the near neighbours, and there are 256 possible simple local rules [26]. This system thus mimics the physics of a causally closed system subject to local dynamical laws. An initial state is specified, for example a random scatter of filled cells, and the array is evolved forward in discrete time steps. A variety of interesting behaviour results. Crucially, the conventional automaton retains the ancient dynamical dualism: the update rules are always independent of the states.

As a first departure from the conventional prescription, we decided to start with a random input state and tried switching between two different rules either randomly or periodically. The results of one interesting case are shown in Figs. 28.1–28.3. This features two automata, designated 87 and 90 according to Wolfram’s classification scheme [26]. Applied on its own, rule 87 leads to structured, but relatively dull, quasi-periodic spatial structures that move across the array at uniform speed (Fig. 28.1). Rule 90 merely perpetuates the random noise (Fig. 28.2). Thus, individually, rules 87 and 90 do not lead to interesting dynamical behaviour. However, when the rules are interspersed, the story is very different. Figure 28.3 shows the outcome when rule 90 is applied and interrupted every seven steps by rule 87. The upshot is the evolution of a form of organized complexity from disorganized, or random, input. Although there is nothing explicitly teleological in the set-up, a form of directionality – order out of chaos – is discerned. With a bit of experimentation, this rule-interspersion technique can be used to combine order and chaos in a suggestively creative manner, getting ‘the

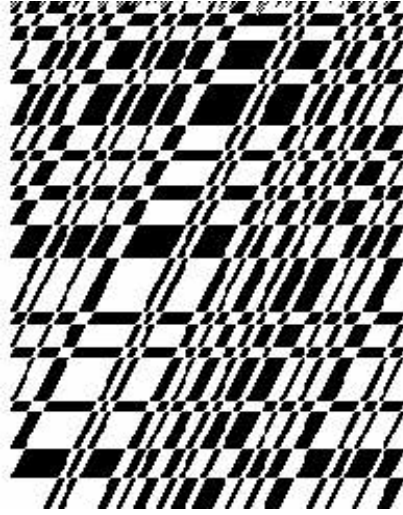


Fig. 28.1. Rule 87 cellular automaton with random initial state. Time runs downward.

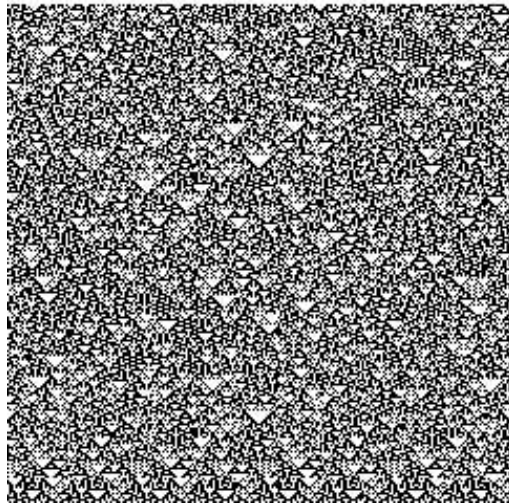


Fig. 28.2. Rule 90 cellular automaton with random initial state.

best of both worlds' – the unpredictability and novelty of chaos with the coherence of order. Our results are reminiscent of Parrondo's games [27], in which two games of chance, each of which when played individually have an expectation of loss, when combined can lead to an expectation of gain. Parrondo's games show that, counter-intuitively, two losses can make a win. Figures 28.1–28.3 appear to be a cellular automaton analogue.

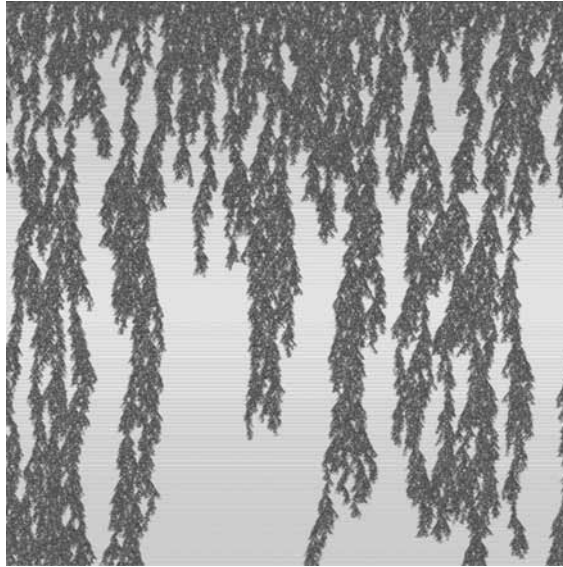


Fig. 28.3. Rule 90 interrupted every seven steps by rule 87 cellular automaton with random initial state.

To incorporate fully my ‘third way’ idea, we must alter the automaton rules so that they depend explicitly on some aspect of the state. To take a very simple example of state-dependent laws, the rule may be chosen to be A if the total number of filled pixels is even and B if it is odd. Alternatively, some statistical measure, such as the entropy or complexity (defined by some prescription) may be used as the discriminator of the rules. Whatever choice is made, the behaviour of a group of pixels now depends not only on the state of the neighbouring pixels, in analogy with conventional physical laws, but on the *global state too*. This is therefore an explicit form of *top-down*, or whole-part, causation [25]. Although our work is at a preliminary stage, the hope is that simple mathematical models might capture the elusive notion that certain complex states are favoured by acting as attractors in the product-space of states and laws. This idea could be placed in a restricted multiverse context by considering how some universes, or regions thereof, generate their bio-friendly laws in an evolutionary sense, and thus become observed. So biology does not actually select a pre-ordained universe; rather, physics and biology co-evolve under the action of a (precise) principle operating at the multiverse level, in such a manner that teleological behaviour emerges. So this is a theory in which life and mind, goal and purpose, arise in a law-like manner from a dynamic universe (or multiverse). The key feature is that there is *a causal link between laws and product states*

(in contrast to Darwinian evolution, where mutations and selection events form causally disjoint chains). Thus life is neither a statistical fluke in an indifferently random set of laws/universes, nor is the Universe designed in an *ad hoc* way for life. Instead, life and mind, laws and universes, are common products of an overarching principle.

If I were to pick a symbol to characterize this set of still rather woolly ideas, it is that of a self-consistent, self-supporting loop. It has some elements in common with Wheeler's idea of a loop in which nature and observer are mutually enfolded [23]. I have described it as a 'turtle loop' in the context of the famous 'tower of turtles' metaphor [28].

As a final illustration of an implicit loop, consider the fact that the mathematics describing the underlying laws of physics is a product of the human mind. The mental realm occupies a conceptually higher level than the physical realm of particles and fields to which this mathematics applies. Why should something created at this higher level apply so famously well [29] to the physical realm? Why should 'software' apply to 'hardware'? More specifically, the concept of what constitutes a computable function (software) is based on the idea of a classical Turing machine (hardware). As stressed by David Deutsch [30], the existence of such a physical device depends on the specific nature of the laws of physics. Thus the concept of computability depends on what the physics of the particular world allows to be computed. So the laws of the Universe permit the existence of physical systems (human beings, Turing machines) that can output the mathematics of those very same laws. This remarkable self-consistent loop is by no means guaranteed [28]. (It also constitutes a further example of why human beings are more than mere observers, which I considered in Section 28.3.3. Human beings are also 'computers'.) There could be many universes with computable laws that do not admit physical systems which can actually output the computable functions describing those laws. Or there could be universes with non-computable laws [31]. Since there is an intimate connection [12] between Turing machines and self-reproducing machines (i.e. life), we glimpse a link between life and laws.

References

- [1] J. D. Barrow and F. J. Tipler. *The Anthropic Cosmological Principle* (Oxford: Oxford University Press, 1986).
- [2] B. Carter. Large number coincidences and the anthropic principle in cosmology. In *Confrontation of Cosmological Theory with Observational Data*, ed. M. Longair (Dordrecht: Reidel, 1974), pp. 291–298.

- [3] M. J. Rees. Numerical coincidences and tuning in cosmology. *Astrophys. Space Sci.* **285** (2003), 375.
- [4] S. W. Hawking. *A Brief History of Time* (New York: Bantam, 1988), p. 174.
- [5] M. Tegmark. Parallel universes. In *Science and Ultimate Reality*, eds. J. D. Barrow, P. C. W. Davies and C. Harper (Cambridge: Cambridge University Press, 2003).
- [6] R. Swinburne. *The Coherence of Theism*, revised edn (Oxford: Clarendon Library of Logic and Philosophy, Clarendon Press, 1993).
- [7] R. Dawkins. *The Blind Watchmaker* (New York: Norton, 1986).
- [8] M. Li and P. Vitanyi. *An Introduction to Kolmogorov Complexity and its Applications* (New York: Springer-Verlag, 1997).
- [9] J. Haught. *What is God?* (New York: Paulist Press, 1986).
- [10] K. Ward. *God, Chance and Necessity* (Oxford: Oneworld, 1996).
- [11] P. C. W. Davies. *The Mind of God* (London and New York: Simon & Schuster, 1992).
- [12] W. Poundstone. *The Recursive Universe* (Oxford: Oxford University Press, 1985).
- [13] R. Penrose. *The Emperor's New Mind* (Oxford: Oxford University Press, 1989).
- [14] N. Bostrom. Are you living in a computer simulation? *Phil. Quart.* **53** (2003), 243.
- [15] M. Brooks. Life's a sim and then you're deleted. *New Scientist* (27 July 2002), p. 48.
- [16] M. J. Rees. *Our Cosmic Habitat* (Princeton: Princeton University Press, 2001).
- [17] L. Smolin. Did the universe evolve? *Class. Quantum Gravity* **9** (1995), 173.
- [18] R. Holder. *God, the Multiverse and Everything: Modern Cosmology and the Argument from Design* (Aldershot: Aldgate, 2004).
- [19] R. Shapiro. *Origins: A Skeptic's Guide to the Creation of Life on Earth* (New York: Summit Books, 1986).
- [20] S. Fox. Prebiotic roots of informed protein synthesis. In *The Roots of Modern Biochemistry*, eds. H. Kleinhauf, H. von Doren and L. Jaenicke (Berlin: De Gruyter, 1988), p. 897.
- [21] C. de Duve. *Vital Dust* (New York: Basic Books, 1995).
- [22] S. Kauffman. *At Home in the Universe* (Oxford: Oxford University Press, 1995).
- [23] J. A. Wheeler. Beyond the black hole. In *Some Strangeness in the Proportion*, ed. H. Woolf (Reading, MA: Addison-Wesley, 1980), p. 341.
- [24] J. Monod. *Chance and Necessity*, trans. A. Wainhouse (London: Collins, 1971), p. 145.
- [25] P. C. W. Davies. The physics of downward causation. In *The Re-emergence of Emergence*, eds. P. Clayton and P. C. W. Davies (Oxford: Oxford University Press, 2006).
- [26] S. Wolfram. *A New Kind of Science* (Champaign, IL: Wolfram Media Inc., 2002).
- [27] J. M. R. Parrondo. Reversible ratchets as Brownian particles in an adiabatically changing periodic potential. *Phys. Rev.* **E 57** (1998), 7297.
- [28] P. C. W. Davies. Why is the physical world so comprehensible? In *Complexity, Entropy and the Physics of Information*, SFI Studies in the

- Sciences of Complexity, vol. VIII, ed. W. H. Zurek (New York: Addison-Wesley, 1990), p. 61.
- [29] E. Wigner. The unreasonable effectiveness of mathematics in the natural sciences. *Commun. Pure Appl. Math.* **13** (1960), 1.
 - [30] D. Deutsch. Quantum theory, the Church–Turing principle and the universal quantum computer. *Proc. Roy. Soc. A* **400** (1985), 97.
 - [31] J. Hartle. Excess baggage. In *Particle Physics and the Universe: Essays in Honor of Gell-Mann*, ed. J. Schwarz (Cambridge: Cambridge University Press, 1991).

